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Analysis of Modern

Hydro-Electric Developments

Electrical Engineering

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ANALYSIS OF MODERN HYDRO-ELECTRIC DEVELOPMENTS

BY

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I. Introduction.

The estimated available water power in the United States is *31,040,000 h.p. minimum, *56,146,000 h.p, maximum. This is based on the assumption of 75% of joint efficiency of the prime mover and generator. The minimum value has been based on the average of the two lowest seven-day periods in each year during a period of seven years, and the maximum, upon the continuous power indicated by the stream flow during six months of the year showing the highest flow. No storage was considered in either estimate. Basing an estimate on every available storage facility it can be assumed that about *200,000,000 h.p. can be ultimately developed. The total water power of the United States which is already developed or under development June, 1911, is given in round numbers as approximately *6,000,000 h.p.

As seen from the above figures, a very large amount of water power is being wasted at present. Since the majority of Hydro-electric power sites which are under construction or undeveloped are as a rule isolated geographicaly or are at least usually far away from the market, the power needs to be transmitted and consequently the problem of Hydro-electric development are of as much interest to Mechanical, and Civil Engineers as to Electrical Engineer.

Since the primary purpose of this thesis is to study the recent progress of Hydro-electric systems from the Electrical Engineering point of view, only a few statements are made of the

problems which are of special interest to the Civil and Mechanical engineers. The basis of study has been largely published data on recent Hydro-electric system installed in the United States.

Important detailes are given under proper headings.

*Figures are taken from D.C. Rushmore's paper in G. E. Review, June, 1912.

II. General Consideration.

1. Determination of the rating of a power plant.

The available power of a Hydro- Electric plant is of course a function of the amount of water and the head. The estimation of the available quantity of water is frequently difficult, while the available head can be determined with considerable accuracy. The best method of estimating the quantity of water is by direct measurment of the flow. This should be taken during all seasons for many years; but a fair approximation can be made from reliable data regarding rainfall, drainage, area, and percentage run-off. The rainfall may be obtaind from the Weather Bureau. The drainage area can be determined from a map; but the runoff is very difficult to assume because it is always affected by many elements such as character of the soil, condition of vegetation, presence of snow or ice, etc. The details on the determination of these quantities can be obtained in almost any book on Hydraulic Engineering, for instance "Water Power Engineering" by Mead. Suffice it to say here that the accurate estimation of the quantity of water is greatest important not only because it is the basis for determination of the rating of the generating plant, but because the dam, the intake, and the tailrace, depend directly thereupon.

A few of the fundamental relations will be given below.

The effective head = the available head - lossof head.

The loss of head is expressed as follows:

loss of head in ft. $= k\frac{l}{d}V^2$, or $=k\frac{l}{q}v^{\frac{5}{2}}$

where, k = constant,

l = length of penstock,

d = diameter of penstock,

q = quantity of water,

v = velocity of water, in penstock in ft.per sec.

When q and l are fixed the loss of head is proportional to the $v^{\frac{5}{2}}$. Large speed means large loss of head and smaller penstock or smaller investment for a given quantity of water. In general, the range from 5 feet to 12 feet per second according to the head is recommended as a proper velocity of water in the penstock. (see table I.)

$$\text{The total out-put h.p. of plant} = \frac{q.\ w.\ H,\ e}{550}$$

where , q = water quantity in cu. ft. per sec.,

w = weight of water in lbs. per cu. ft.,

H = effective head in ft.,

e = joint efficiency of plant.

The factor e which varies with the size of the generating unit,and it can be obtained from the manufacturer of the generator and prime mover. A few examples will be seen in table I.

2. Determination of Transmission Voltage.

The economical size of conductor of a transmission line is a function of voltage and the amount of power to be transmitted; but independent of the distance of transmission, as it will be shown later on. The amount of power to be transmitted is determined by the condition of the market. The question bearing directly on the transmission is one of greatest importance and in the decision about the best construction the following items should

Table I.

Designation of plant.	Effective head in feet.	Velocity of water in the penstock ft. per sec.	Prime Mover h.p. rating.	%, eff.	Joint Eff. of the plant in %.
A	49	8.7	6,000	*92	88
B	1,100	6.0	3,000		
C	40		4,150	85	79.5
D	34		3,200		
E	100		5,500		
F	170	9.0	9,000		
G	245	10.0	6,400	84	78.6
H	115	9.0	4,000	84	78.5
I	525	17.5	18,000	87	83.5
J	105	11.0	6,000	86	80.5
K	1,100		6,000		
L	46	8.3	2,000	81.5	77.0
M	300	5.0	1,750		
N	487	8.0	7,000	82	77
O					
P	53	6.0	13,500		
Q	81	8.5	6,000	81	76
R	440	12.0	18,000	90	86
S	72	5.0	5,200	80	74.5
T	145	8.5	18,500	86	82
U	610		8,000		
V	73	7.5	11,000	88.5	83.5
W	90		13,000		
X	200	6.6	3,750		
Y	1,410		6,100		

be considered.

The cost of energy lost in the conductor for year.

The proper annual charge against the conductor.

The proper annual charge against the line support.

The proper annual charge against the transformer.

The proper annual charge against the auxiliary apparatus.

Let;

c_e be the market price of power per k.w. year at the low tension main of the substation,

x be the load factor,

p be the full load power at the generating station in k. w. which is to be transmitted in one direction,

E be the line voltage in k,v. at the generating station,

$\cos\theta$ be the average power factor,

r be the resistance of conductor in ohms per circular mil mile,

w be the weight of conductor in lbs. per circular mil mile,

L be the length of the transmission line in miles,

A be the area of conductor in circular mils,

c_c be the cost of conductor per lbs.,

p_c be the annual charge on the capital out-lay of conductor,

C_1 be the total cost of power lost in the conductor for year

C_2 be the total annual expense of the conductor for a year,

then,

$$C_1 = c_e \cdot p, x = c_e\left[\frac{p}{\sqrt{3}\, E\cos\theta}\right]^2 \frac{3.r.L,x}{1000A} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

$$C_2 = 3.c_c.w.L.A.p_c \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

According to Kelvin's Law, C_1 is equal to C_2 or:

$$c_e\left[\frac{p}{E.\cos\theta}\right]^2 \times \frac{r.L.x}{1000A} = 3c_c.w.L.A.p$$

$$A = \frac{p}{E.\cos\theta}\sqrt{\frac{c_e.r.x}{3000c_c.w.p_c}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Substituting (3) to (1) and (2),

$$c_1 = \frac{p.L\sqrt{3000c_c.w.p_c.c_e.r.x}}{1000E.\cos\theta} = \frac{1}{E}K_1 \quad . \quad . \quad . \quad . \quad . \quad (4),$$

$$c_2 = \frac{p.L.3\sqrt{c_e.r.x.c_c.w.p_c}}{E.\cos\theta\ 3000} = \frac{1}{E}K_2 \quad . \quad . \quad . \quad . \quad . \quad (5).$$

The cost of pole or tower is of course independent of the voltage. The cost of the insulator can be assumed to be proportional to the voltage without material error.

Let;

c_p be the cost of one wooden or steel pole or a tower,

c_i be the cost of one insulator per k.v,

p_p, p_i be the rate of interest and depreciation of pole, insulator respectively,

s be the average span of poles in mile,

n be the number of circuits to the one direction,

then,

$$C_3 = p_p, c_p\frac{L}{s} + 3n.p_i.c_i\frac{L}{s}E = K_3' + K_3.E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

The cost of transformer and auxiliary apparatus is difficult to express by mathematical equation. Dr. Sheldon says in his book "E lectric Traction and Transmission" that the former may be express in the following equation (7) approximately for such a size as usual in transmission system, and the latter is about proportional to the voltage. The writer found these equations are quite accurate in many instances.

Let;

p_1 be the capacity of single transformer in k.w.,

p_t, p_a be the rate of interest and depreciation of transformer, auxiliary apparatus respectively,

c_t be the cost of one transformer,

k_1, k_2 be the constant depending upon the manufacturer,

n_1, n_2 be no. of transformers in the power station, in the substation respectively,

c_a be the cost of one set of auxiliary apparatus in both of power station and substation, per k.v.,

C_4 be the annual charge against the total cost of transformers,

C_5 be the annual charge against the total cost of auxiliary apparatus,

n_3 be the no. of sets of auxiliary apparatus in both of power station and substation.

Then $$c_t = (k_1 \cdot E + k_2)\sqrt{p_1} \quad \ldots\ldots\ldots\ldots\ldots \quad (7),$$

$$C_4 = n_1 \cdot p_t (k_1 \cdot E + k_2)\sqrt{\frac{p}{n_1}} + n_2 \cdot p_t (k_1 \cdot E + k_2)\sqrt{\frac{p}{n_2}}$$

$$= k_1 \cdot p_t (\sqrt{n_1} + \sqrt{n_2}) E\sqrt{p} + k_2 \cdot p_t (\sqrt{n_1} + \sqrt{n_2})\sqrt{p}$$

$$= K_4 \cdot E + K_4' \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8),$$

and $$C_5 = p_a \cdot n_3 \cdot c_a \cdot E = K_5 \cdot E \quad \ldots\ldots\ldots\ldots\ldots \quad (9).$$

Total annual expense, $C = C_1 + C_2 + C_3 + C_4 + C_5$, substituting each value of C_1, C_2, C_3, C_4, C_5,

$$C = \frac{1}{E} K_1 + \frac{1}{E} K_2 + K_3 \cdot E + K_3' + K_4 \cdot E + K_4' + K_5 \cdot E$$

To get the minimum value of, C,

$$\frac{dC}{dE} = 0 = -\frac{1}{E^2}(K_1 + K_2) + K_3 + K_4 + K_5 ,$$

$$E = \sqrt{\frac{K_1 + K_2}{K_3 + K_4 + K_5}} \quad \ldots\ldots\ldots\ldots\ldots \quad (10).$$

This is then the equation of most economical transmission voltage, where

$$K_1 = \frac{p.L\sqrt{3000c_c.w.p_c.c_e.r.x}}{1000\cos\theta},$$

$$K_2 = \frac{p.L\sqrt{3c_e.r.x.c_c.w.p_c}}{\cos\theta\sqrt{3000}},$$

$$K_1 + K_2 = K = \left[\frac{0.11p.L\sqrt{c_e.r.x.c_c.w.p_c}}{\cos\theta}\right],$$

$$K_3 = 3n.p_i.c_i\frac{L}{s},$$

$$K_4 = k_1.p_t(\sqrt{n_1}+\sqrt{n_2})\,p,$$

$$K_5 = p_a.n_3.c_a.$$

The following values of the constants represent pretty closely recent practice.

$\cos\theta = .85$,	$p_c = .06$,
$r = 56,000$ for copper,	$p_i = p_t = p_a = .12$,
$x = .4$,	$c_i = .20$\$*,
$c_c = .15$\$ for copper,	$k_1 = .50$\$*.
$w = .016$ lbs., for copper,	$c_a = 80$\$**,
$c_e = \$50.00$,	

* taken from Dr. Sheldon's "Electric Traction and Transmission",

** calculated basing of two low tension oil switches, two high tension oil switches, two sets of disconnecting switches, three choke coils and four stacks of alminum cells.

The curves (plate I.) show the most economical voltages, for an average high tension transmission systems, they are calculated

by the equation (10) using above constants. It is assumed, as it is the case generally, that the transmission system has two sets of lines on one pole line and two sets of transformer banks and one transformer as a spare on each end of transmission line.

Then; $n = 2,\ n_2 = n_1 = 7,\ n_3 = 4,$

$$K = \frac{0.11p.L}{\cos\theta}\sqrt{c_e.r.x.c_c.w.p_c}$$

$$= \frac{0.11p.L}{.85}\sqrt{50\times 56,000\times .4\times .15\times .016\times .06}$$

$$= 1.64p.L,$$

$$K_3 = 3n.p_i.c_i.L/s = 6\times 12\times .2\times 10\ L = 1.5L,$$

$$K_4 = k_1.p_t(\sqrt{n_1}+\sqrt{n_2})\sqrt{p} = .5\times .12\times 2\sqrt{7}\times\sqrt{p}$$

$$= .32\sqrt{p},$$

$$K_5 = p_a.n_3.c_a = .12\times 4\times 80 = 38.4,$$

$$E = \sqrt{\frac{K}{K_3+K_4+K_5}} = \sqrt{\frac{1.64p.L}{1.5L+.32\sqrt{p}+38.4}}\quad .$$

Table II gives the value of E for different L and p.

TABLE II.

p p	L= 15,	30,	45,	60,	75,	100,	125,	150,	200,	250,	300,	500.
2,500	28	35	39	41	43.5	45	46	47	48	49	50	51
5,000	39	48	54	57	60	62.5	64	66	68	69	70	71
7,500	45	58	64	69	72.5	75	78	80.0	82	83	84	87
10,000	52	65	73	78	82	86	90	91.5	94	95	96	100
15,000	61	77	87	94	91.5	104	108	110	114	116	118	122
20,000	68	87	99	107	112	118	123	126	130	134	136	140
25,000	74	96	109	117	124	131	136	140	145	149	152	156
30,000	80	103	117	127	134	142	148	152	157	161	164	170
50,000	96	126	143	157	167	178	185	191	200	205	210	218
100,000	123	164	186	206	220	238	250	260	273	283	289	304

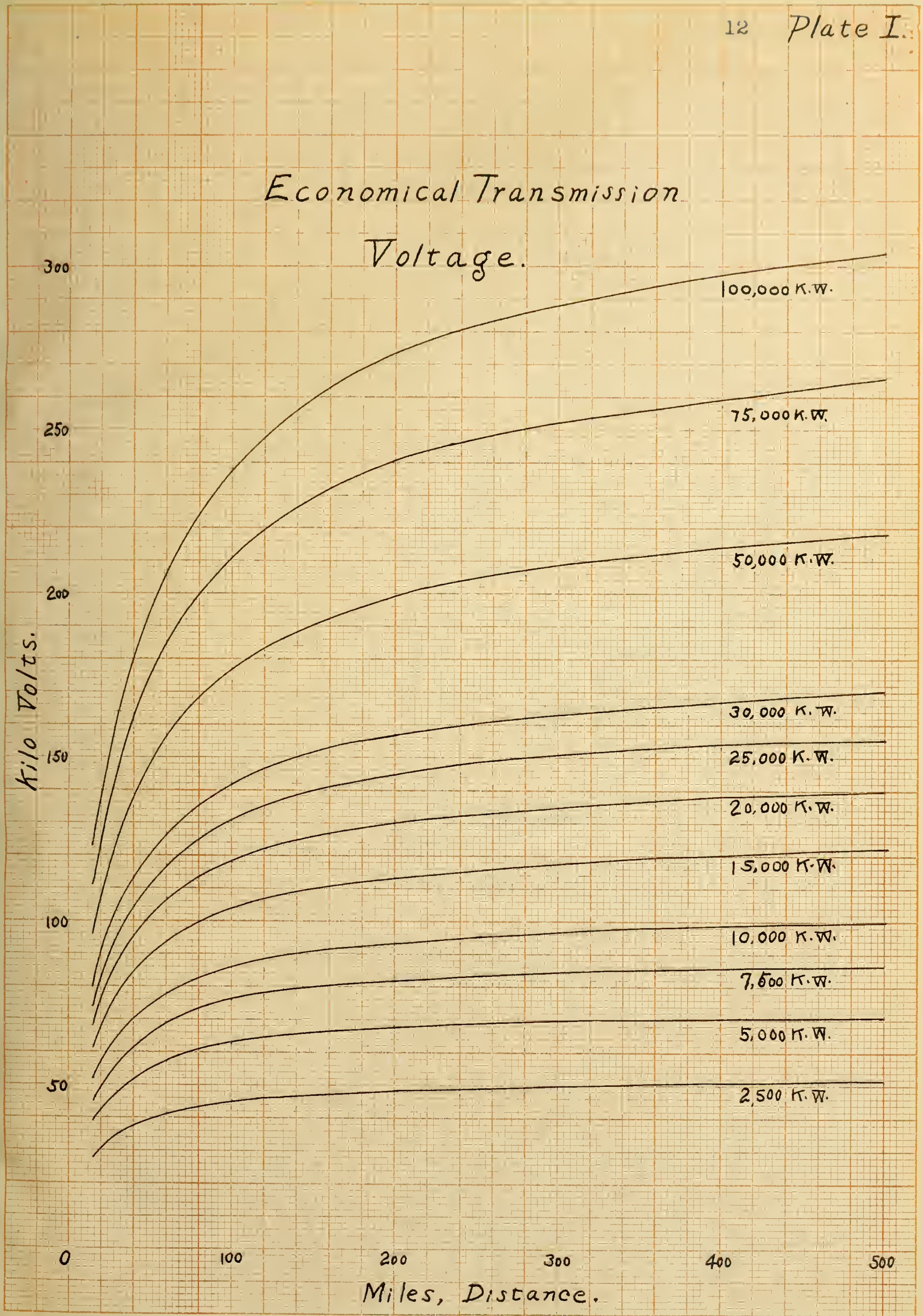
Above values are plotted in curves in the plate I, page 12.

As higher and higher transmission voltages are demanded the difficulties increase both for the manufacturer who has to design a transformer and for the engineer who has to design the line and keep it in operation. The limit may be reached by the corona loss due to desruption of the air surrouding the transmission wire. Yet we must remember that it is only a few years ago when 30 kilo-volts was the highest commercial transmission voltage while now transmission line of 140 kilo-volts is in successful operation since last year. The curve in the plate II shows the increase in transmission voltage since the three phase alternating current transmission system, at 2,000 volts, has born in the United States in 1894. But the transmission voltage is really limited by economical consideration. As seen in preceeding table II and plate I, it is about the same for transmission of a given power over any distance as long as we are considering long distance transmissions.

Table III gives the comparison of voltages of existing ~~tra~~ transmission system and the calculated economical voltage.

3. The most suitable frequency of transmission systems.

The standard frequencies in the United States are 60 cycles and 25 cycles. The former frequency envolves as a rule cheaper machines except possibly in the case of rotary convertors and commutator motors. It is much preferable for lighting, but it is not as satisfactory as the latter frequency in connection with large synchronous motors and rotary convertors. This often objectionable, also, on account of the large charging current taken by the line. 25 cycles seems to be about as high frequency as


12
Plate I.
Economical Transmission
Voltage.
100,000 K.W.
75,000 K.W.
50,000 K.W.
30,000 K.W.
25,000 K.W.
20,000 K.W.
15,000 K.W.
10,000 K.W.
7,500 K.W.
5,000 K.W.
2,500 K.W.
Kilo Volts.
300
250
200
150
100
50
0
100
200
300
400
500
Miles, Distance.

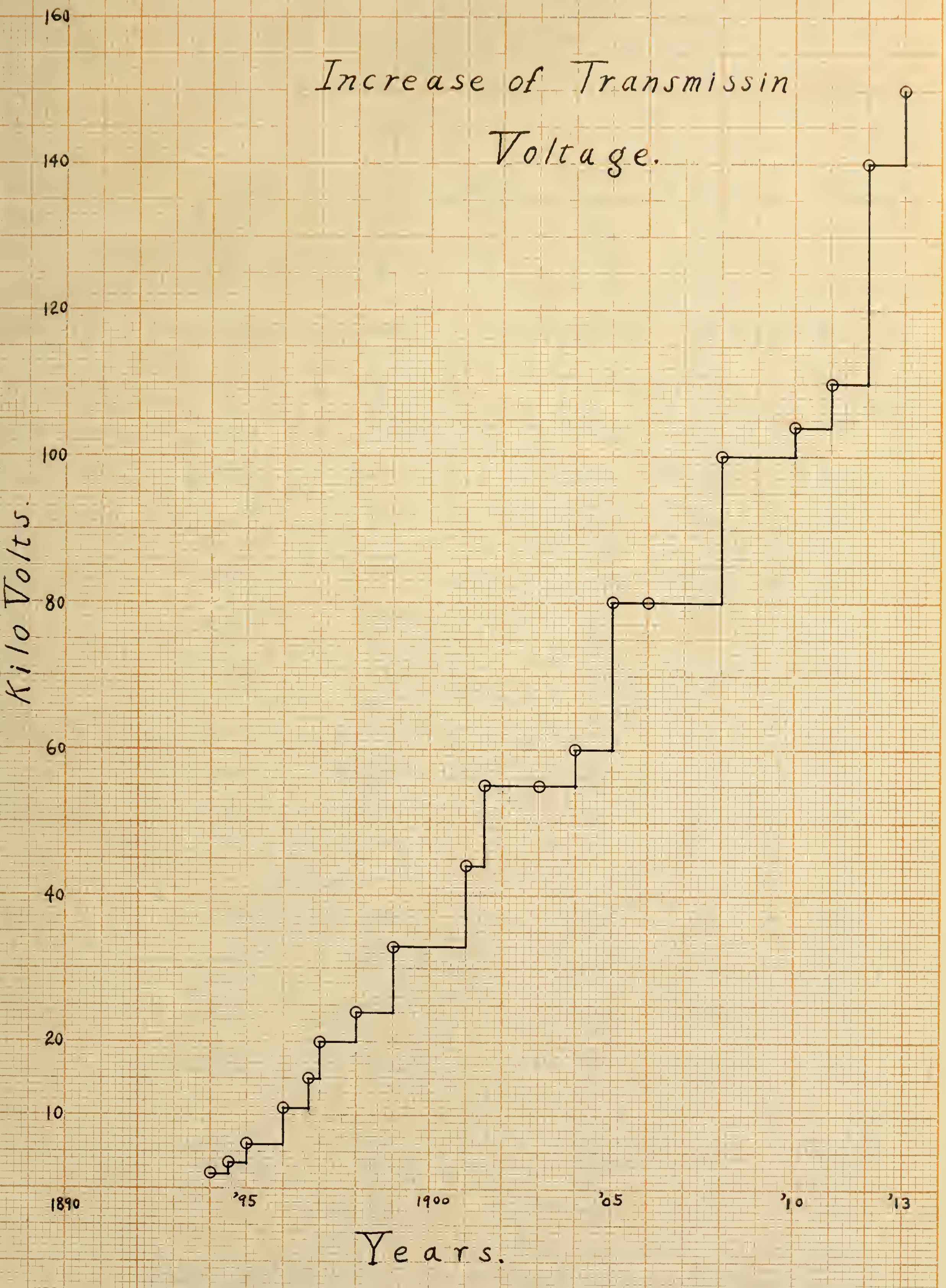

Increase of Transmissin
Voltage.
Kilo Volts.
160
140
120
100
80
60
40
20
10
1890
'95
1900
'05
'10
'13
Years.

Table III. Transmission voltage.

Designation of plant.	Power to be transmit. to one direct. k.w.	Distance of transmission. present. miles.	feat.	Transmission voltage k.v. pract.	calcu.	Frequency
A	10000	65	110	88	80	60
B		70				
C	9000	125	225	140	91	60
D	10000	66		66	80	60
E	10000	34		66	68	60
F	10000	153		100	92	60
G	6600	27		57	53	60
H	8400	28		60	60	25
I	20000	137		100	124	60
J	21000	130		102	127	60
K	8000	45		60	66	60
L	5000	38.5		33	51	60
M	5000	11		22	34	60
N						
O	*8000	*106	200	110	79	25
P	40000	40		70	127	25
Q						
R	10000	26		55	62	60
S	*8000	*145	200	100	82	60
T	28000	87		100	134	60
U	11000	39		69	73	60
V						
W	15000	32		60	79	60
X	3750	42		45	49	60
Y		37		60		60

*taken average of all circuit emanating from station.

can give saisfaction for alternating current railway service, and at present time 15 or 25 cycles is used. The cost and the weight of electric machine as function of frequency is given by Mr. D.B. Rushmore of General Electric Co, in the paper of A.I.E.E. June, 1912.

Finally the natural frequency must be considered, it is:

$$f_n = \frac{7900}{\sqrt{L.C}} ,$$

where L is the total inductance of the circuit in milliheries and C the total capacity in microfarads. From the above equation it is easily found that for instance 150 miles transmission line has a natural frequency of about 300 which corsesponds to the fifth harmonic in a 60 cycles system. (See table III, page 14, for examples of frequency is used in practice.)

III. Generating System.

1. Prime Mover and Governor.

Two types of water turbine are used in Hydro-electric stations. They are the tangential or impulse turbine and reaction turbine. The necessary conditions imposed on a water turbine are of course, high efficiency, lowest cost, durability,and good speed regulation. These depend largely on the capacity of the turbine. The capacity of ~~of~~ the turbine is determined from the ultimate output of the plant and load condition. The lesser number of units - the larger the capacity of each - as a rule the efficiency is the higher. The units must not be too large , however, since in that case the plant efficiency may suffer at light load. Practical examples are shown in table IV.* Each case must, however, of course be treated individually.

Efficiency. To obtain good efficiency of water wheel cafeful design and workmanship are necssary. It is well known that the highest efficiency of water turbine will be given when the peripheral speed of wheel is one-half of spouting velocity of the water. The spouting velocity of the water is equal to $\sqrt{2gh}$; where g is acceleration of gravity, h is effective head. Thus the sfficiency of water turbine depends on the effective head, and variation,in either way, of the effective head lessens the efficiency. Since constant speed is demanded in hydro-electric plants and usually, the effective head is not constant, but varies from time to time and from season to season. A careful investigation

*page, 23.

of the variation of head ought to be made before the turbine is chosen. The effective head under which the turbine shall operate must be determined so as to ensure the highest efficiency for each particular case. An interesting example of the engineers,necessary when the variation of effective head is large,is given(see example D). It is seen that a runner of smaller diameter, which is running idle in normal condition, in order to get the maximum out-put when the effective head is extremly reduced.

Speed. The high speed turbine is desirable on account of the saving in cost of generator, but the speed of water turbine has of course a fairly fixed relation to its h.p. and effective haed. The term "specific speed", that is number of R.P.M. of the wheel to develope one h.p. under a foot head, is used to discuss the speed of water turbine.

$$\text{Specific speed, } K = \frac{N \sqrt{h.p.}}{H \sqrt[4]{H}},$$

where N = no. of R.P.M.

h.p. = horse power of the turbine,

H = effective head in ft.

The value of K is not fixed, it varies with the design, it is higher for low head reaction turbine than for high head reaction turbine, and much lower for impulse turbines. Different values of K are given below.

From "Water power Engineering" of Prof. D.W. Mead;

for reaction wheels 11.5 min., 86 max.,

for impulse wheels 2.0 min., 4.25 max.,

From the paper of Coldwell before the A.I.E.E. in April, 1912; for reaction wheels:- K Max. effective head.

K	Max. effective head. in feet.
68 - 75	50
50 - 68	100
35 - 50	200
25 - 35	400
10 - 25	600

Relations between K and efficiency are shown in following Figs:-

Fig. 1.

Efficiency curves for various values of K, full load eff. as 100%.

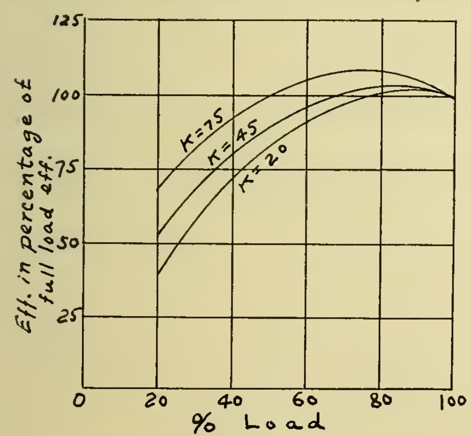
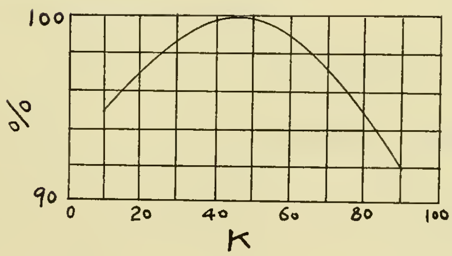


Fig. 2.

Variation of the efficiency according to the values of K, highest eff. as 100%.



The standard values of Allis-Chalmers Co.:-

K = 13.55 for reaction turbine under head of 205 - 600ft.

K = 20.3 " " " " " " 150 - 470ft.

K = 29.4 " " " " " " 80 - 350ft.

K = 40.7 " " " " " " 50 - 150ft.

The values of K, given above, are not fixed and are merely given as aguide.

The run-away speed of water turbine is also important since the speed of water turbine is depends on the velocity of the spouting water, the peripheral speed can be expressed in percentage of the velocity of the spouting water or $U = \phi\sqrt{2 g H}$.

where, U = peripheral speed at extreme of the wheel,

ϕ = constant,

g = acceleration of gravity,

H = effective head.

From the fundamental theory of hydraulics, it is known that the linear speed of water wheel should be one half of the velocity of the spouting water, for maximum efficiency of the wheel. The linear velocity is not the speed at the extrem of the circumference of the wheel but it is the speed at a point where the center of spouting water is acting. The value of ϕ for impulse wheel is pretty close to .5, because the water shoots the wheel practically at its peripheral and the direction of the motion of wheel is in the same with the direction of the spouting water. The value of ϕ for reaction wheel varies from about .55 to about .9 according to the shape of the vane of the wheel. The maximum input to the wheel is equal to the product of the force acting at the entrance and the speed of the wheel at entrance.

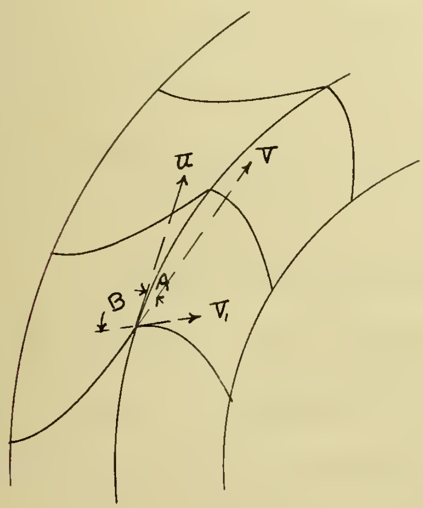


Fig. 3.

$$\text{Input to the wheel} = U \frac{w}{g} V \cos A$$

where,

U = peripheral velocity of the wheel,

w = total weight of the water flowing,

V = velocity of the wheel at the entrance.

Neglecting mechanical and hydraulic losses in wheel,

$$e\,w\,H = U\,w/g\,V \cos A.$$

$$U = e\,g\,H \frac{1}{V \cos A}$$

where e = efficiency of turbine,

H = effective head.

From the triangle of velocity, $V \sin(A + B) = U \sin B$.

Substituting the value of V to preceeding equation,

$$U^2 = e\,g\,H \frac{\sin(A + B)}{\sin B \cos A},$$

or

$$U = c\sqrt{H}\sqrt{\frac{\sin(A \quad B)}{\sin B \cos A}} = \phi\sqrt{2\,g\,H}$$

As seen above, a certain relation exists between U, e and angles A, B. Butit is not within the scope of this thesis to discuss the relation in detail. Suffice it to notice that the runaway speed is different according to the normal value of ϕ.

Let $\phi_r = \phi_{max.}/\phi_{normal}$, ϕ_r guaranteed by Allis Chalmers Co, are:

1.85 for $\phi_n = 0.585$

1.73 for $\phi_n = 0.70$.

The paper of Prof. Mead befor A.I.E.E. in June, 1912, gives

$\phi_r = 1.5$ to 1.85 for recation wheel,

$\phi_r = 1.4$ to 2.1 for impulse wheel.

All figures mentioned above, are based on the constant head. But in practice, the effective head may increase due to surging, so that it seems conservative in each case to require a double speed guarantee of machines from the manufacturer.

Ratio of h. p. of turbine to k.w. out put of generator- C. Since water turbine are generally rated on their maximum output under maximum head a proper allowance should be made for the limiting conditions in load and head. It is evident that the so called

capacity of the turbine has really no fixed relation to k.w. rating of generator. Steadiness of head, character of load, and over-load capacity of the generator are the conditions which determine the rating. This is clearly seen from the figures in plate III page 22, which gives the relation between the turbine and generator ratings. It is very evident that the efficiency curve must be studied before the relation is determined. Refere the table IV * for the value of C.

The most suitable type, the reaction or impulse type, is not easy to determine in case of medium head. In the early days 300 ft. head was the limit for the reaction turbines on account of the dificulty of runner construction which high velocities, the limit is now more nearly 600 ft. which is fortunate since the reaction type appears to have advantages over the impulse type. The following figures are given as a rough guide in the selection of the type of water turbine.

	k,w. out put of Generator.								
	200	300	500	1000	2000	3000	5000	7500	10000
max. head for reaction turbine. ft.	150	200	300	350	400	500	600	600	600

Regulation of speed. Constant speed of the electric generators is important though to be serve by the use of automatic voltage regulator it is not absolute necessary. The variation of speed is of course caused by the unbalancing between the counter torque and the supplying torque. The counter torque is proportional to the power taken by the generator. Consequently the variation of counter torque will be expressed by the following equation.

$$T = T_0 \varepsilon^{\alpha t}.$$

*page 23.

Fig. 1.

Typical Efficiecy Curve of Water Turbine.

A-- Generator rating allowing 25 % overload.
B-- " " " 15 % overload.

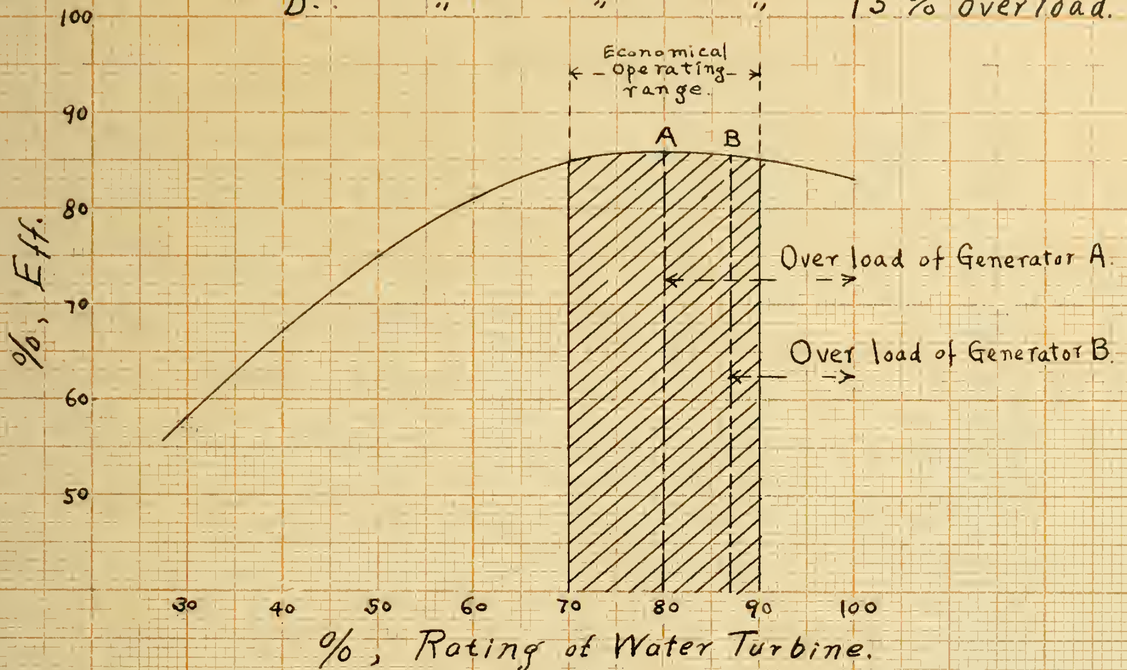


Fig. 2.

Typical Eff. Curves.

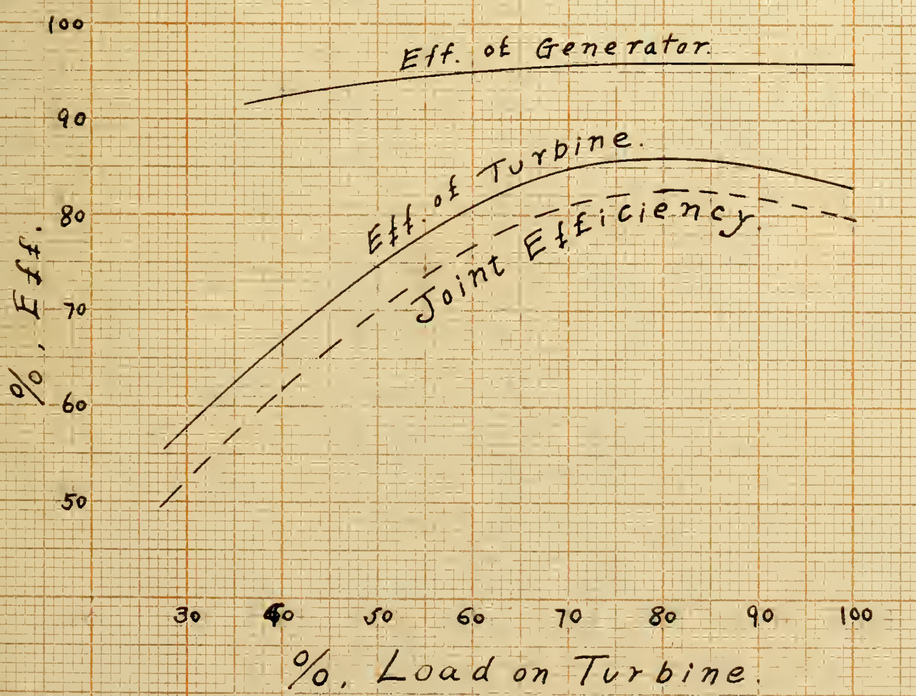


Table IV.

1=Designation of plant, 2= Head in ft.,3=Ultimate h.p. of plant, 4=H.P. of turbine, 5=R.P.M., 6= k, 7=No, of wheels, 8=Dia. of wheel 9=   , 10=K.V.A. of generator, 11=K.V.A./H.P. of turbine.

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
A	49		5000	116	68	1		.75	4000	1.5
B	1100	9000	3000[i]	400	3.4	1			1800	1.66
C	40	12450	4150	180	57.5	4			3000	1.38
D	34			133		1 2	*57" 60	.75	2500	
E	100	25000	5500	300	49.7	2	39"	.64	3000	1.83
F	170	18000	9000	400	44	2			5000	1.8
G	245	38400	6400	514	42.7	1			3750	1.7
H	115	12000	4000	300	50.	1			2800	1.43
I	525	144000	18000	400	21.3	1			10000	1.8
J	105	36000	6000	225	36.4	2			3500	1.71
K	1100	12000	6000[i]	400	4.85	1			4000	1.5
L	46	10000	2000	200	74.5	1	52".5	.51	1400	1.43
M	300	7000	1750	720	24.2	1			1250	1.4
N	487		7000	450	16.8	1	54"	.60	4000	1.75
O										
P	53	135000	13500	94	54	2	115".5	.745	10000	1.75
Q	81	30000	6000	240	54	2	51"	.74	3667	1.64
R	440	108000	18000	360	23.7	1			10000	1.80
S	72		5200	225	55	2	52".5	.765	3000	1.67
T	145	80000	18500	225	43	2			14000	1.32
U	610		(2400[i] (8000	600 400	4.9 12	2 1			5000	1.6
V	73		11000	150	52	2	74"	.71	5550	1.98
W	90	52000	13000	225	65.8	2			7500	1.73
X	200		3750						2500	1.5
Y	1410		6100[i]	400	3.6	1			4000	1.53

i--impulse wheel.   * Running idel in normal head.

where T = final counter torque after tsec.,

T_o= initial counter torque,

ϵ = base of natural logarism,

t = time,

α = transient factor depends upon the circuit condition.

It is thus necessary for ideal speed regulation that the supplying torque shall change at the rate shown above. But that is almost impossible in practice because the change inthe torque supplied is obtained by the mechanical governor which can not reach instantly due to its inertia. It is therefore necessary to be satisfied with some degree of departure from the normal speed and some lag of time of regulation. Much theoretical discussion is necessary to understand the principle of the governor but it is not within the scope of this paper. A very importance is the pressure regulation, specialy for plants of high head with the requirmentsof the governor to be sensitive and quick acting, sudden and often very great pressure are suddenly imposed on the penstock. But important as this plase is it can obviously not be dealt with here.

2. Generator.

Capacity of unit and its speed. These considerations closely connected with prime mover, and has really been dealt with in connection with them. A noticiable recent development in generator construction for hydro-electric purposes, in connection with low head are extrem low turbine speed is the introduction of gearless turbine even in large size as illustrated for instance with the 9000 k.w. 57 r.p.m. generators at KEOKUK Plant of Missi-

ssippi Pr.Co., and the 300 k.w. 72 r.p.m. at Rock River Plant, Ill.

Voltage of the Generator. The highest terminal voltage of A.C. generator in commercial use is 19,000 volts in one plant in California while 30,000 volts generator are used in the Continent. The high voltage generator seems advantageous for where power is delivered a moderate distance only. It seems reasonable to expect that a 19,000 volts generator should be satisfactory and by obtaining the transmission voltage directly - transformers are not necessary. The usual difficulty with high voltage generator is however short life of insulation of the armature coil. It is decidedly difficult to build up insulation so as to preclude any air and if such exists microscopic discharges take place, because the potential gradient in that air becomes large owing to the thick insulating material, which has high specific inductive capacity, and therefore throws the strain on the air. Asa matter of fact this phenemenon does not seem to cause much trouble yet be must remember that it might exist and if so it continuous through all time of service. There are indeed some instance in which this has caused breakdown, where it has been found that the electric conductor had decomposed chemically. The above is no doubt the reason why many good authority recommend low voltage generator for transmission systems. Refere table V, page 29.

Regulation and efficiency. The deffinition of the regulation of an alternating current generator is.

$$\text{regulation} = \frac{E - e}{e},$$

where E = terminal voltage at open circuit,

e = " " " non inductive full load with constant excitation.

To obtain good regulation of the generator, high saturation, considerable air gap, etc., are the necessary conditions. A generator with poor regulation may be built with lower core loss and less weight it will always be cheaper than a closely regulation machine. Since devices for obtaining automatic voltage controll have been perfected during the last few years the inherent regulation of the generator has become of minor importance and generators with high efficiency are supplied. Poor regulation means increase in synchronous reactance, and reduction of the short circuit currnt.

Wave form of E.M.F. of the Generator. The E.M.F. wave of a generator always differs from a sine wave. It consists, as is well known, of a combination of the fundamental sine wave and waves of higher frequencies. Effects of higher harmonics, if they exist in and are of considerable magnitude, are important in transmission system since they may cause reasonance. The third harmonic usually causing mischief in single phase circuit can fortunatelynot exist inthe three phase system which can have only the fifth, seventh, eleventh, etc. The causes of higher harmonics are the lack of sinisoidal destribution of the field flux, hysteretic destortion, variation of the magnetic reluctance, and pulsation of flux due to the armature slots. The designing engineer is always trying to improve the wave form and much success has been met with largely by , properly shaping of the pole piece, fractional pitch winding, and proper numbers of slots per pole per phase, etc. For detail about this refer to a paper in the proceeding of A.I.E.E. in Feberuary, 1913 which gives an interesting discussin for practical engineers.

Effect of short circuit. Trnaient value of short circuiting current in three phase generator may be expressed in following equation.

$$i = \frac{E}{x}\left[\varepsilon^{-\frac{r_o}{x_o}(\theta-\theta_1)}\sin(\theta-\beta)(1-k)\frac{X}{Z} - \varepsilon^{-\frac{r}{x}(\theta-\theta_1)}(1-k)\sin(\theta_1-\beta)\frac{X}{Z} - \frac{kx}{z_1}\sin(\theta_1-\beta_1) + \frac{kx}{z_1}\sin(\theta-\beta)\right]$$

Where, E = nominal induced E.M.F. per phase,

x = self inductive reactance reactance in out side of generator,

r_o= effective resistancoof generator field circuit,

x_o= self inductive reactanc of " " " ,

z = synchronous impedance of generator,

$\beta = \tan^{-1}\frac{X}{R}$ $\qquad \frac{R}{X} = \frac{r}{x} - \frac{r_o}{x_o}$

$\beta_1 = \tan^{-1}\frac{x}{r}$

z_1 = self inductive impedance of generator,

$k = z_1/z$

θ_1 = phase angle at which generator shorted,

ε = base of natural logarism.

The maximum value of the short circuit current may in water wheel turbo-generator will be over ten times the rated normal current. But this large current exists for a very short instant indeed so that it does not cause any damage to the generator itself, and it is of interest to the practical engineer to know the value of the permanent short circuit current.

I = permenent short circuit current,

$$= \frac{E}{z + z_2}$$

z_2 = impedance of out side circuit.

Since with large units z is small, z_2 also may be small

containing frequently only the impedance of the transformer, it is often necessary to limit short circuiting current by extra reactance coil while however this is importance with steam turbine units, it is really not very important for generators considered here. Before leaving this subject however it should be noted with a short circuit on the A. C. generator a rush current exists in the exciter circuit and the exciter may flash over.

3. Excitation system.

There are three methods for excitation a. c. generators; self excitation, composite excitation, and separate excitation.

The latter method is used almost entirely. The necessary exciting energy depends on the capacity and the speed of the generator. The voltage of excitation depends upon the field construction of the generator. Slow speed generators with number of poles need as a rule higher excitation voltage than machines of lesser number - although it is not essential. 125 volts and 250 volts, however, are standard voltages of the exciters in this country. Sometimes the exciters are shunt wound sometimes compound wound, there is apparently little choice between them. The size of the exciter depends upon the total power required for excitation of the plant. There appears to be six systems of exciter arrangement used in hydro-electric plants.

a. Direct coupled or geared exciter to the generator shaft, its capacity being just enough for the generator,

b. Same driving method as a, but its capacity being for two or more generators,

c. One or two exciters for the entire system, driven by independent prime mover,

Table V.

Designa. of plant.	Ulti.k.w.	No. of units, present.	Unit capacity. k.v.a.	Trans. volts k.v.	Genera. volts	R.P.M.	Freq.
A		4	4000	88	13200	116	60
B	7000	3	1800		2300	400	60
C	9000	3	3000	140	2500	180	60
D	20000	8	2500	66	2300	133	60
E	18000	6	3000	60	2300	300	60
F	10000	2	5000	100	4000	400	60
G	23500	4	3750	57	6600	514	60
H	8400	2	2800	60	2300	300	25
I	100000	4	10000	100	10000	400	60
J	21000	6	3500	102	6600	225	60
K	9000	2	4000	60	2300	400	60
L	7500	5	1400	33	2200	200	60
M	5250	4	1250	22	2300	720	60
N		3	4000	66	6600	450	60
O							
P	100000	3 1 2	10000	70	11000	94	25
Q	22500	5	3667	55	11000	240	60
R	80000	6	10000	65	6600	360	60
S		6	3000	100	2200	225	60
T	60000	4	14000	100	6600	225	60
U		(2 2	1500 5000	60	2300	600 400	60
V		4	5550	66	4000	150	60
W	40000	2	7500	60	4000	225	60
X		(1 1	1250 2500	45	2300		60
Y		4	4000	60	2300	400	60

d. Motor generator sets,with other small exciter of capacity just enough to start the plant,

e. Combination of c and d,

f. Mortor generator sets, one of which having a extended shaft and coupled to a prime mover with removable coupling.

The advantages and disadvantages of above systems can be understand without any further discussion. Comparative study should of course be made before deciding on what system of arrangement to choose in each specific case. The detail of the systems and exciting circuit are thoroughly dicussed in the proceeding of A,I.E.E.,july, 1912 by Mr. Rushmore. For examples of practice see table VI. page 31.

4. Transformer.

The transformer is a most important item in the transmission systems at the present day. It is indeed frequently the weakest link in the high tension transmission system, especially so since the developments of the suspension insulator and alminum lightning arrester. Unfortunately the dificulties apparently increases with increasing size - resonance phenomena inside of the winding take place which are practically impossible in smaller units due to the lesser capacity in the windings.

The regulation of the transformer is more important than that of the generator because automatic regulation cannot be provided so simply. This is thereason why the manufacturer has made every effort to improve the regulation of transformer and up-to-date transformer may be built with 1% or less % of regulation. But, it should be borne in mind that the low reactace of the transformer produces large starting current, or large short circuit

Table VI.

Plant.	Total k.w. of excits.	Exci.Pr, per.k.w. of gen.	No. of excits.	Exci. volts.	Kinds of driving.
A	500	.031	2	250	water wheel.
C	156	.0173	3	125	mounted on gene. shaft.
B					
D	600	.03	2	110	water wheel.
E	750	.042	3	250	2 - water wheel, 1 - motor.
F	240	.024	2		mounted on gene. shaft.
G	300	.020	2		water wheel.
H	250	.045	2	125	1 - water wheel, 1 - motor.
I	400	.0125	2	250	water wheel.
J					mounted on gen. shaft.
K			1		motor & water wheel on each end.
L	240	.034	2	125	water wheel.
M	100	.0266	2		1- water wheel, 1- motor.
N	450	.0375	2	125	water wheel.
O					
P	1300	.033	3	250	800 k.w. water wheel, 500 " motor.
Q	245	.022	4	125	3-mounted on gen.shaft. 1- motor.
R	450	.0224	2	250	water wheel, one has a motor on extended shaft
S	500	.0278	2	250	" " . " " " " " " ".
T	800	.0286	2	125	one water wheel, one motor.
U					
V	480	.0216	4	250	mouted on gen.shaft.
W	500	.0333	2		water wheel.
X	100	.0266	2	125	1 - water wheel, 1 - motor.
Y	300	.0188	3	250	1 - W. h., 1-motor, 1 - w. h.& motor.

current . Abnormal current in transformer produce large mechanical strain as well as electrical strain between primary and secondary coils. Mechanical force between two coils is proportional to the product of self inductive flux and current, so the mechanical force increases proportionally to the square of the current. The short circuit current is discussed under the heading of the generator. The starting current of the transformer can be calculated by the step-by-step method; voltage, number of turns, magnetic characteristic of the core being known. Such method is thoroughly described in G.E. Review, page 650, 1912, by Dr. Berg; or see "Transient Electric phenomena" of Dr. Steinmetz, Chapter XII.

Three phase transformer and single phase transformer.

The advantages of the single transformer are: Saving in first cost of spare apparatus and less weight of each unit. The former reason is always pointed out, strongly, and it is indeed of importance, neverthless a careful comparative study must be made between the single phase and three phase transformer before a choice is made. The three phase transformer has often many advantages in particular cases. These are, higher efficiency, cheaper cost, less weight, simplicity of high tension wiring and cooling system, and the saving of the construction cost of the transformer compartment and the floor space. Such savings make often the total investment of the system smaller even when three phase transformer is kept as spare. The three phase transformer as can three single phase transformer be used in open delta connection in emergency, if it is specified with the manufacturer.

Cooling of transformer. The oil insulated water cooled type is used almost entirely for high potential transmissionsystem. For

medium voltage transformer forced air cooling may be used.

Connection of Transformer.

There are essentially three different ways in which to connect transformers for transmission systems; namely the delta connection, grounded neutral Y connection with or without resistance between neutral and ground, and the insulated neutral Y connection.

The choice of connection continues to be discussed by prominent electrical engineers and is by no means settled.

The Y conection with grounded neutral seems preferable from the point of view of protection of the system against abnormal potential because this connection maintains the normal potential to ground under usual operating conditions. The strongest objection to it is that the service becomes interrupted when a short circuit, due to any earthing of a line, occurs. This very weakness of the grounded Y connection is the strongest argument on favor of the delta connection. Its weakness on the other hand is that great possibility exists for rise in potential between line and ground. If a line is grounded the maximum potential in the system is increased 73% above normal. Further-more almost any disturbance in the system such as induced static potential may cause a rise in potential, limited only by the discharge voltage of the protecting apparatus. When a arcing ground occurs in a line of delta connection it will continue until the trouble is found although it may introduce dangerous high frequency oscillations.

With the grounded neutral Y connection, however the circuit in that case will be opened by the circuit breaker. Since the introduction of the "arc suppresser" this difficult of the delta connection is however almost entirely eliminated.

It appears that both systems today are used indiscriminately. Briefly it seems to the writer that the delta connection is necessary when the continuety of the service is very important as when only one transmission line runs from the station to the recieving station; the grounded neutral Y connection is in general preferable. When the grounded neutral system is used a resistance in series may be used to limit the current to earth. But this is not good plan because the potential rises to the Y voltage plus the voltage drop in the resistance used.

The ungrounded neutral Y connection is used in some cases. The writer found four examples. It should be borne in mind, if such connection is necessary, that there is risk of an abnormal rise of potential when one phase of the primary opens accidentally. The reason for this is that when one phase of the primary is open circuited no voltage is induced in the corresponding phase of the secondary and the other phases become the source of power for supplying the inductance of the secondary coil of the defective phase and the capacity of the line in series. In this way an abnormal potential may be introduced.

Table VII.

Plant.	genera. capaci. k.v.a.	Trans. capaci. k.v.a.	Voltage, low. vol.	high. k.v.	Phase	connection.
A	2300 4000	6000	13200	88	three	
B						
C	3000	3000	2500	140	three	delta
D	2500	5000	2300	66	"	Y,g.
E	3000	3000	2300	66	"	
F	5000	3330	4000	100	single	delta,
G	3750	3000	6600	57	"	Y,
H	2800	2800	2300	60	three	delta.
I	10000	10000	11000	100	"	"
J	3500	1200	6600	102	single	"
K	4000	1400	2300	60	"	Y,G.
L	1400	1400	2300	33	three	Y.
M	1250	500	2300	22	single	
N	4000	4000	6600	66	three	Y.
O						
P	10000	10000	11000	70	three	Y.g.
Q	3667	3667	11000	57	"	Y.
R	10000	3333	6600	55	single	delta.
S				100		Y.g.
T	14000	14000	6600	100	three	" "
U	1500 5000	1500	2300	60	single	" "
V	5550	5550	4000	63	three	" "
W	7500	3000	4000	60	single	
X						
Y	4000	1500	2300	60	single	Y.g.

g--grounded.

IIII. Transmission Line.

1. General.

The choice of transmission voltage, has already been discussed. Thsi paragraph will therefore deal largely with the study of electrical and mechanical characterisitics of the transmission line - physical constant and construction detail. The hight of conductor above the ground is of minor importance from electrical stand point and is decide from cosideration of public safty. The minimum distance above the groun by common consent is apparently 20 ft. Thespacing between conductor is governed by practical considerations although to be sure the electrical constants the inductance, and capacity, the natural frequency and the corona loss depend thereupon. Following figures are widely used in this country.

voltage between line. in k.v.	spacing bet. line. in inches.
30	48
60	72
90	96
120	120

Inductance.

The inductance is the interlinkage of magnetic flux with the current in the conductor, that is

$$L = \Phi/i$$

L = inductance,

Φ = flux interlinks,

i = current,.

For two parallel conductor,

$$\Phi = \int_{r}^{D} \frac{2\mu i}{x} dx + \int_{0}^{r} \frac{2\mu_1 i\ x^3}{r^4} dx = L\ i \quad ,$$

if $\mu = \mu_1 = 1$

$$L = 2 \log_e D/r + 1/2,$$

or $L = \left[2 \log_e D/r + 1/2\right] 10^{-9}$ henries per cm.,

$L = \left[7.41 \log_{10} D/r + .805\right] 10^{-4}$ henries per mile of a wire.

$= 7.41 \times 10^{-4} \log_{10} 1.285 D/r$

where D = distance between the wires,

r = radius of the wire.

The inductance of a wire cable is somewhat different it is

for 7 strand wire $L = \left[7.41 \log_{10} 1.38 D/r\right] \times 10^{-4}$ *

19 strand wire $L = \left[7.41 \log_{10} 1.32 D/r\right] \times 10^{-4}$ *

The inductive drop is

$e = L\ 2\pi f\ I$ volts per phase,

$e = \sqrt{3}\ L\ 2\pi f\ I$ volts between line of the three phase,

when L is the inductance in henrys and when the three conductors are arranged at corners of an equilateral triangle.

If the three conductors are arranged horizonyally or vertically the inductance of each conductor is not the same, therefore the inductive drop of each phase is different unless the conductors are transposed as shown in figure 4.

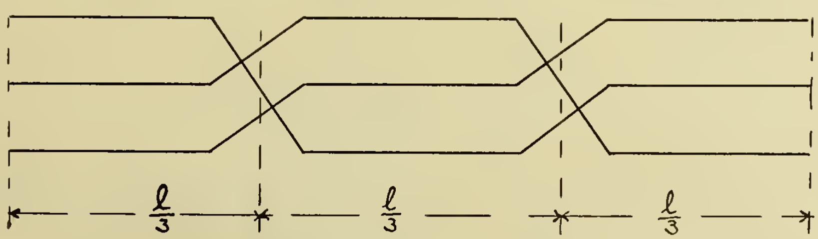


Fig. 4.

The inductive drop of the middle phase is $2\pi f L I$ while it is $2\pi f L_0 I$ in other two phases, where

$$L = \left[7.41 \log_{10} 2D/r + .805\right] \times 10^{-4} \text{ henrys per mile of a wire,}$$

$$L_0 = \left[7.41 \log_{10} D/r + .805\right] \times 10^{-4} \quad " \quad " \quad " \quad " \quad " \quad " .$$

L_t = inductance when wires are transposed,

$$= \left[\tfrac{2}{3}(7.41 \log_{10}\frac{D}{r} + .805) + \tfrac{1}{3}(7.41 \log_{10}\frac{2D}{r} + .805)\right] 10^{-4}$$

$$= 7.41 \left[\log_{10} 1.435D/r\right] 10^{-4}.$$

Capacity.

A close approximation of the capacity of two parallel conductors is ;

$$C = \frac{1}{4 \log_e (D-r)/r} \text{ in electro static unit,}$$

or

$$C = \frac{0.00368}{\log_{10} D/r} \text{ m.f. per 1000 ft of circuit,}$$

or if the capacity is refered to a single wire to the ground it is

$$C = \frac{0.00736}{\log_{10} D/r}$$

The capacity of the three phase system, it obtained in the usual way and is

$$C = \frac{1}{\log_e \dfrac{D^2\ 4\ h^2}{r^2(4h^2 + D^2)}}$$

where h = hight of conductor above ground.

Since D^2 is small compared with $4\ h^2$ we get:

$$C = \frac{1}{2 \log_e D/r}$$

$$\text{or} \quad C = \frac{0.00736}{\log_{10} D/r} \text{ m.f. per 1000 ft of a wire.}$$

(Note that inobtaining the charging current the voltage to the neutral should be used.)

If the conductors are not arranged symmetrically, the equation of the capacity is much more complicated. Fortunately there is a convenient method of obtaining a fair approximate in such complicated circuit, that is

$$v = \frac{1}{\sqrt{L_o C_o}}$$

where v = velocity of propagation = $3\ 10^{10}$,

L_o = inductance per unit length,

C_o = capacity " " " ,

$$\text{or}\quad C_o = \frac{1}{v^2 L_o}\ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (a)$$

The value of L_o is readly obtained, it is :

$$L_o = 2 \log_e D/r + 1/2$$

neglecting the second term, becaues it is the term due to the flux inside of the conductor, and substituting to the equation (a) we get:

$$C_o = \frac{1}{v^2 2 \log_e D/r} \text{ per wire in C.G.S. unit,}$$

$$\text{or}\quad C_o = \frac{0.00736}{\log_{10} D/r}.$$

This is the same as the equation given previously.

Regulation.

The regulation of transmission line is defined as the ratio of the voltage variation between no load and full load(non inductive) to the full load voltage at the recieving end. Its value is determined from the general equation governing the flow of power of an inductive circuit.

Let, E_o = voltage at generating end,

E = " " recieving end,

I_o, I = current at generating and recieving end respectively

$Z = r - jx$ = impedance of the line,

$Y = g + jb$ = admittance of the line,

$= + jb$ practically, g being very small quantity,

$Z_1 = r_1 - jx_1$ = impedance of recieving circuit,

$Y_1 = g_1 + jb_1$ = admittance of the recieving circuit.

Approximations:

(A) Short line in which the capacity may be negrected,

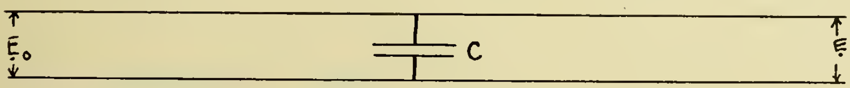
$$I_o = I = E_o\left[g + j(b + b_1)\right] = E(g + jb)$$

$$E_o = E\left[1 + (r - jx)(g + jb)\right]$$

*(B) Line capacity represented by one condenser shuted across the middle of line,

$$I_o = E\left\{\left[g + 1/2b(rb_1 - xg_1)\right] + j\left[(b_1 - b) - 1/2b(rg_1 + xb_1)\right]\right\}$$

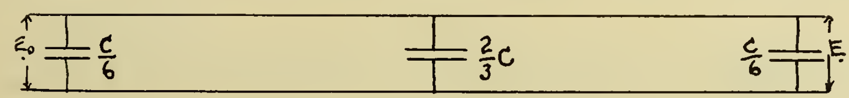
$$E_o = E\left\{1 + (r - jx)(g_1 + jb_1 - jb/2) - jb/4(r - jx)^2(g_1 + jb_1)\right\}$$



*(C) Line capacity represented by three condensers, in the middle and at the ends of the line,

$$I_o = E\left\{\left[g + \frac{b}{2}(rb_1 - xg_1)\right] + j\left[(b_1 - b) - \frac{b}{2}(rg_1 + xb_1)\right] - \frac{b^2}{36}(r - jx)^2(g_1 + jb_1 - jb/6)\right\}$$

$$E_o = E\left\{1 + (r - jx)(g_1 + jb_1 - j\frac{b}{2}) - j\frac{b}{6}(r - jx)^2(g_1 + jb_1 - j\frac{b}{6})\right\}$$



(D) Distributed capacity,

* See "A.C. phenomena" by Dr. Steinmetz, page 228.

$$* \quad \underset{\cdot}{I} = \frac{1}{2}\left(\underset{\cdot}{I}_o + \underset{\cdot}{E}_o\sqrt{\frac{Y}{Z}}\right)\varepsilon^{-\alpha l}(\cos\beta l + j\sin\beta l) + \left(\underset{\cdot}{I}_o - \underset{\cdot}{E}_o\sqrt{\frac{Y}{Z}}\right)\varepsilon^{+\alpha l}(\cos\beta l - j\sin\beta l)$$

$$* \quad \underset{\cdot}{E} = \frac{1}{2}\left(\underset{\cdot}{E}_o + \underset{\cdot}{I}_o\sqrt{\frac{Z}{Y}}\right)\varepsilon^{-\alpha l}(\cos\beta l + j\sin\beta l) + \left(\underset{\cdot}{E}_o - \underset{\cdot}{I}_o\sqrt{\frac{Z}{Y}}\right)\varepsilon^{+\alpha l}(\cos\beta l - j\sin\beta l)$$

In this case, Z, Y, are the values per unit length,

e = base of natural logarithem,

$\alpha = \sqrt{1/2(ZY + r\ g - x\ b)}$

$\beta = \sqrt{1/2(Z\ Y - r\ g + x\ b)}$

l = distance from generator end.

In general, E_o, I, power factor, r,x,b,l, are known and g is nearly equal to zero. Therefore, the voltage and current at any point of line can be found from the above two equations. Above equations are refered to Dr. Steinmetz's works.

The equations in the case (D) can be expressed more simply by applying hyperbolic function,

$$\cos h\ x = 1/2(e^{x} + e^{-x}),$$

$$\sin x\ h = 1/2(e^{x} - e^{-x}),$$

therefore,

$$\underset{\cdot}{I} = \underset{\cdot}{I}_o \cos h(V\ l) - \underset{\cdot}{E}_o\sqrt{\underset{\cdot}{Y}/\underset{\cdot}{Z}}\ \sin h(V\ l),$$

$$\underset{\cdot}{E} = \underset{\cdot}{E}_o \cos h(V\ l) - \underset{\cdot}{I}_o\sqrt{\underset{\cdot}{Y}/\underset{\cdot}{Z}}\ \sin h(V\ l),$$

where $V = \alpha - j\beta$

Natural frequency.

The natural frequecy of a circuit is represented by following equation

$$f_1 = 1/4\sqrt{L\ C}$$

for distributed inductance and capacity circuit, where L is total

inductance of circuit in henry and C is total capacity of circuit in farad.

$$f_1 = \frac{7900}{L_m C_m}$$

$L_m = 2\ (2 \log_e D/r + 1/2)10^{-6} = 1.48 \log_{10} D/r + .161$ m.h. per mile,

$C_m = 0.019/\log_{10} D/r$ micro farad per mile.

Corona loss.

The general form of the equation of the corona loss is;

$$p = k\ f(E - E_c)^2,$$

where p = loss of power in k.w. per unit length of a conductor,

k = constant,

E = voltage of the line to neutral in k.v.,

E_c = critical voltage to neutral in k.v.,

f = frequency per sec;

is recognized basing to many experiments and theoretical study, at present. Different values for k and E_c are given by different engineers, those are mentioned in following:

$$E_c = 21.1\ m_o \frac{3.92B}{273 + T}\ r \log_e \frac{S}{r} \quad \text{by Peek.} \quad . . . . . . (1)$$

$$E_c = .455\alpha \frac{17.9\ b}{459 + t} \frac{d + 2a}{.00736} \log_{10} \frac{S}{r} \quad \text{Prof. Ryan.} \quad . . . (2)$$

where m_o = 0.98 to 0.93 for solid wire,

= 0.87 to 0.83 for seven strand cable,

B = barameter reading in cm.

b = " " " inches,

T = temperature in c°,

t = " " F°,

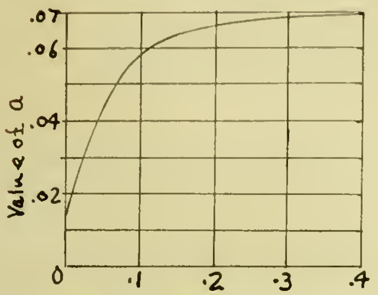
α = 0.72

d = outer diameter of conductor in inches,

r = radius of conductor in cm.,

S = spacing between conductors,

a ---see following curve.



$$k = \frac{10^{-5} \times 344(273 + T)}{3.92\ B} \sqrt{\frac{r}{S}}$$ per k.m. of single coductor,

by Peek. . . . . . (3)

$k = 0.024 \times 10^{-3}$ per mile of single conductor,

by E. Hausmann. . . . . . . (4)

$k = 0.075 \times 10^{-3}$ per mile of single conductor, derived from the data of Faccioli's test. (5)

The curves in plate IV, page 44, are plotted from calculation by different methods from practical data given below.

*Example:-

length of the line:- 27.6 miles of single phase line,

spacing of conductor: 124"= 314cm. for 18.4 miles,

248"= 628 cm. for 9.2 miles,

diameter of conductor: .354"= .898 cm. (7 strand)

barometer reading: 62 cm.= 24.4" average during test,

temperature; 18 c^{o} = 64 F^{o}.

The equation (1) gives slightly larger value than the equation (2). The equation (1) has been used for the caculation of the corona loss because it is rationally and proved by the experiment of Peek.

(1)&(3) A.I.E.E. July, 1911 and June 1912.
(2)&(4) " Jan., 1911
* &(5) " Feb., 1911,

The curves in plate IV show the power loss curve due to corona:

1. is calculated by Peek's equation

$$p = \frac{10^{-5} \times 344(273 + T)}{3.92\ B} \sqrt{\frac{r}{S}}\ f(E - 21.1\ m_o r \log_e S/r)^2 \quad (6)$$

2. is calculated by the equation

$$p = 0.075 \times 10^{-3}\ f\ (E - 21.1\ m_o r \log_e S/r)^2 \ . \ . \ . \ . \ (7)$$

3.*loss due to convection current. This is calculated by the Ryan's equation

$p' = 4 \times 10^{-6} f^2 E^2$ watts per 1000 of single conductor.

where f = frequency,

E = k.v. to the neutral.

4.**results of the test by Faccioli.

Curves 1 and 2 must bend like as dotted line due to the theory of convection current loss and joint to the curve 3, so the curve 2 is pretty close to the result of the test. In the following, another check of formulas is given.

Data:- Test at Au Sable Co!s line.***

Three phase, 6p cycle, 125 miles transmission line,

Spacing ofconductor:-- 200 inches,

Diameter " " .375"(7 strand of 125" dia.) = 953cm.

Results of test:- 80 k.v.a. per mile, in open end circuit,

3000 k.w. for total line of " " " ,

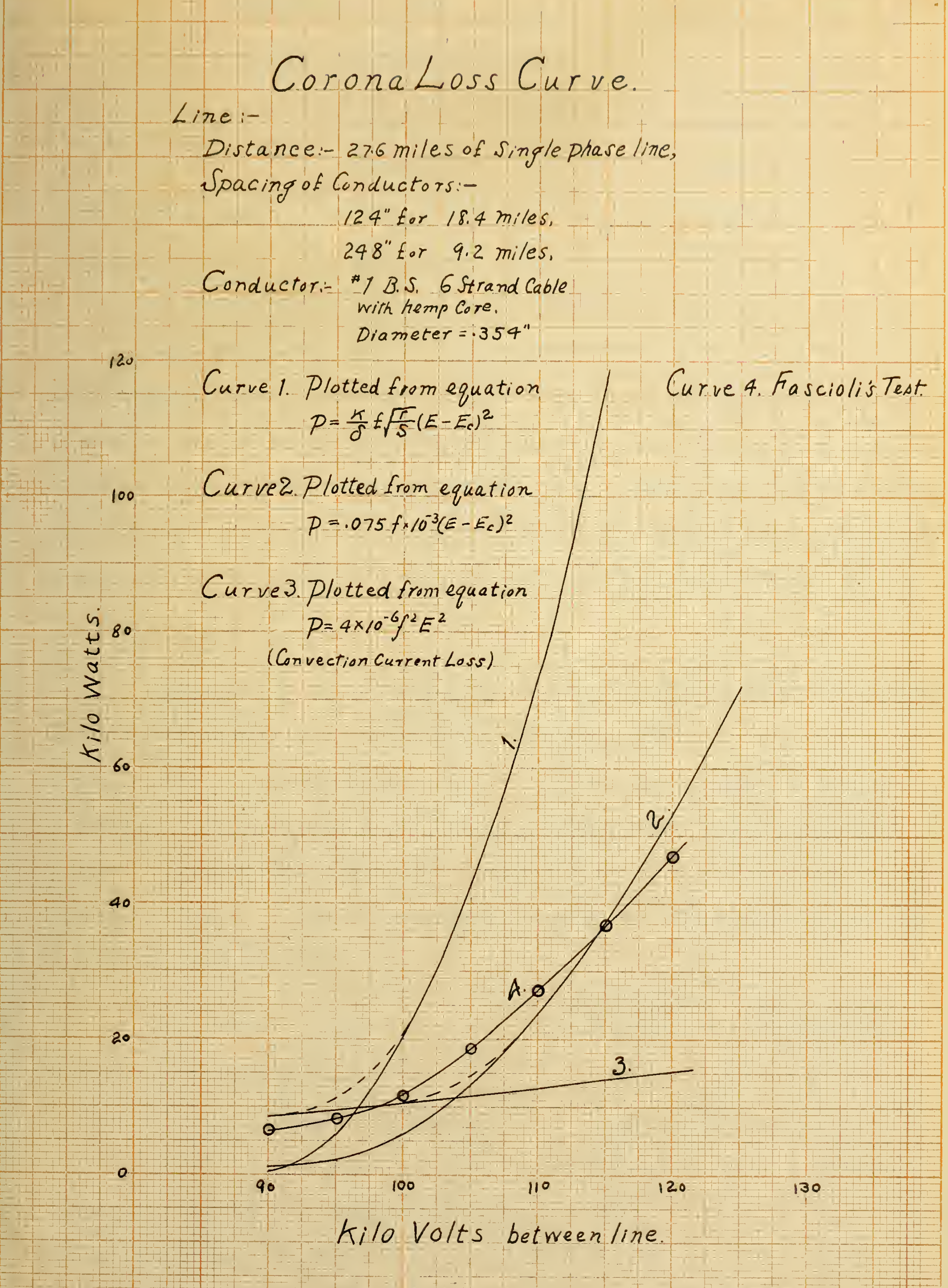
140 k.v. between line when tested,

190 k.v. at the open end, computed.

* Ryan says, in Trans. A.I.E.E. vol. XIX part I, that there are considerable line loss, before corona starts, which is expressed in the above equation, and he call it convection current loss.

** A.I.E.E. Feb., 1911.

*** Elec. World: April 20th, 1912.


Corona Loss Curve.
Line :-
Distance:- 27.6 miles of Single phase line,
Spacing of Conductors:-
124" for 18.4 miles,
248" for 9.2 miles.
Conductor:- #1 B.S. 6 Strand Cable
with hemp Core.
Diameter = .354"
Curve 1. Plotted from equation
$p = \frac{K}{\delta} f \sqrt{\frac{r}{S}} (E - E_c)^2$
Curve 2. Plotted from equation
$p = .075 f \times 10^{-3} (E - E_c)^2$
Curve 3. Plotted from equation
$p = 4 \times 10^{-6} f^2 E^2$
(Convection Current Loss)
Curve 4. Fascioli's Test.
Kilo Watts.
120
100
80
60
40
20
0
1.
2.
3.
A.
90
100
110
120
130
Kilo Volts between line.

Calculations from above data are as following:-

E_c = 59.7 by the equation (1)

	by the equation (6)	by the equation (7)
k . f	.01018	.0045
total corona loss	5700 k.w.	2520 k.w.
total I^2R loss	160 k.w.	160 k.w.
total loss	5860 k.w.	2680 k.w.

As it seen, the equation (7) gives a close approximation.

As a matter of facts, the corone loss is a function of many complicated physical terms, and it seems to be impossible to express it in a simple form for wide range. For instance, Peek's formula is based on many experiment for a long time during different season. Prof. Harding's results agree quite well with Peek's formula but it does not satisfy the examples given above.

2. Conductor.

Three kinds of material of conductor may be used for transmission of electricity - Copper, Aluminum, Iron.

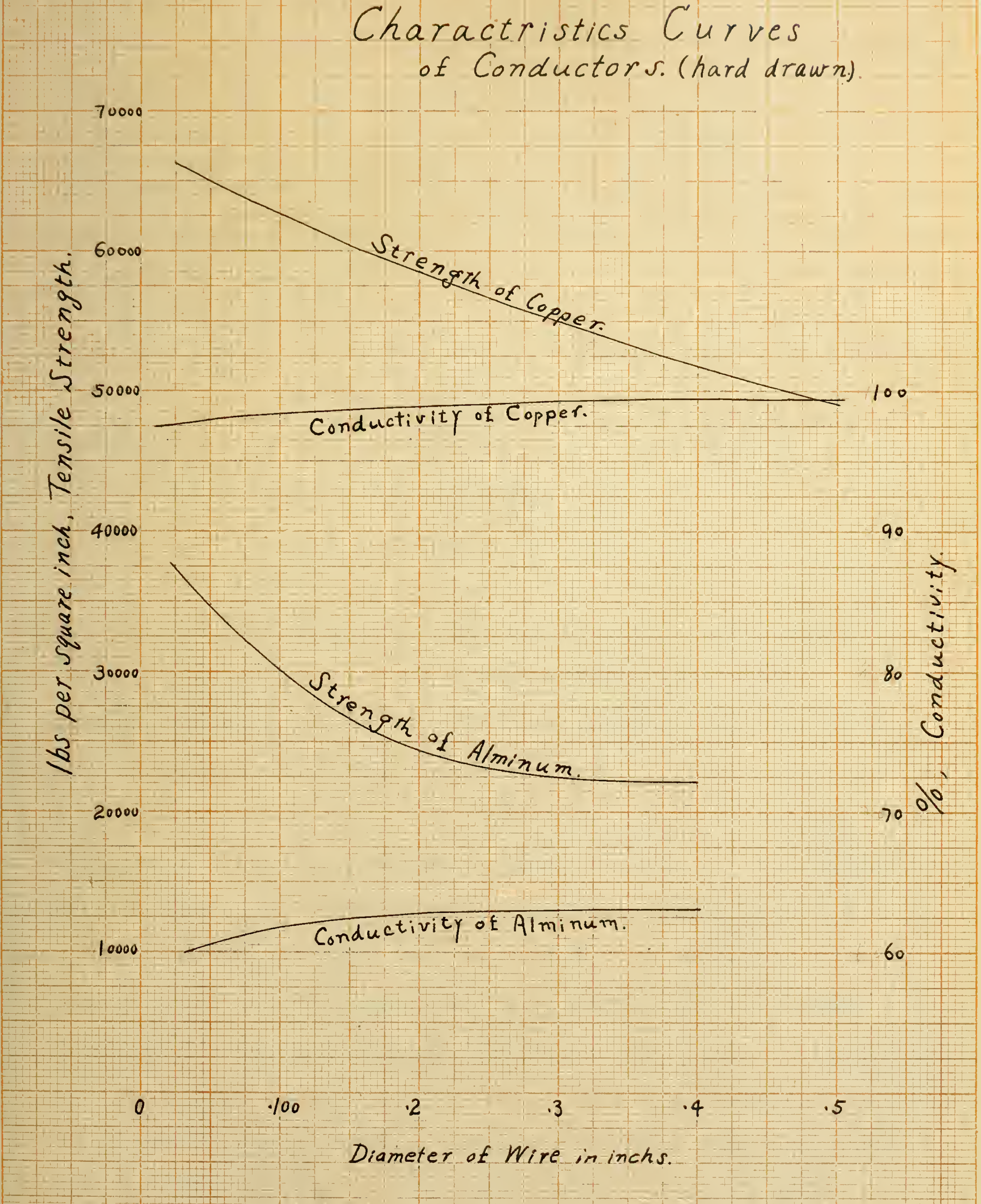
Iron is rarely used except for very small power at high voltage. The properties of iron will therefore not be included here. Copper and Aluminum are used most widely for power transmission lines. Their important properties are mentioned in the following tabulation:

	Hard drawn copper.	Hard drawn aluminum.
Weight in lbs. per cu.in.	0.323	0.0976
" " " " cir. mil ft.	3.027×10^{-6}	0.914×10^{-6}
" " " " " " mile.	0.0161	0.00486
Conductivity in % of Math. standard.	98	62
Resistance in ohms per cir. mil ft.20c°	10.57	16.7

	Hard drawn copper.	Hard drawn aluminum.
Expansion coefficient per F^{O}.	0.0000095	0.0000128
Melting point. F^{O}.	2912	1157

The choice depends really on the relative market price. The aluminum conductor has some advantage that is for a given resistance it has larger diameter, therefore the corona formation occurs at a higher voltage.

Solid conductor and stranded cable. As it seen from curves in plate V, page 47, that the strength and the conductivity of a conductor varies with the size. Stranded cables are now used almost entirely because it have advantages of, flexibility, and easy of handling and slightly greater strength. It should be borne in mind that the strength of stranded cable is not equal to the strength of the individual wires multiplied by the number of elements, because the distribution of stress is not uniform. Experiments indicate that 90 % of theoretical strength may be taken as the true strength of a stranded cable. As an illustration, # 0 B. S. copper solid wire has a tensile strength of 54000 lbs. per sq.inch and the equivalent seven strand copper conductor has 62000 .9 = 55800 lbs. per sq. inch, that is 3.3 % greater strength. In the case of aluminum wire the same analysis would gives 16% increase in strength, therefore stranded cable is always used when aluminum conductor are used. Other characteristics of strand conductor are; decrease of reactance, increase of resistance and corona loss, and increase in wind stress. To improve the distribution of stress in cables hemp cored stranded wire is used. It should be noted,however,that some trouble has been experienced


Charactristics Curves
of Conductors. (hard drawn)
70000
60000
50000
40000
30000
20000
10000
lbs per square inch, Tensile Strength.
Strength of Copper.
Conductivity of Copper.
Strength of Alminum.
Conductivity of Alminum.
100
90
80
70
60
%, Conductivity.
0
·100
·2
·3
·4
·5
Diameter of Wire in inchs.

when using hemp cored stranded wire in high tension transmission system. Evidently corona loss is increased and corrosion of the conductor takes place. The latter is very important, because it may cause the breakage of the wire. The cause of this phenomena is probably the chemical action of free acid which may deposite, on the surface of the conductor, by the discharge of electricity from hemp fringes projecting out of the metal surface. The mechanical force acting on the conductor surface is of some interest in this connedtion.

$F = \frac{2\pi\sigma^2}{445}$ is the mechanical force, acting on the conductor surface, in lbs. per sq. cm.,

where σ = surface intensity in C.G.S. unit $=2Q/r$

Q = charge in the conductor = $C\ e$

r = radius of the conductor in cm.

C = capacity,

e = static potential in C.G.S. unit = 1/300 volt.

As a example, assume a transmission line with 10' = (305 cm) distance between the wires, 100 k.v. between line, and #0 B.S. equivalent 6 strand wire with hemp core. Then it is found that F = .6 lbs. per sq. cm. Of course the pressure between individual wires of a stranded conductor, due to tension of the conductor will prevent the hemp from striking out, under normal condition. The force necessary to pull the hemp out of the conductor is found easily where the tension of the wire, the pitch of strand, and the friction coefficient of hemp and copper are known. If the cable is strung with a safty factor of 2.5 , if the friction coefficient is .2 and if the stranding pitch is 1.5 feet, then the force is 2.3 lbs. per sq. cm. The mechanical force is of course not con-

stant it may be reduced to small fraction of what is given above - indeed it may be in reversed direction by irregular wind stress etc. The electric force is however a constantly acting. This should be seriously and it may suggest the use of a two layers cable - a cable of say 19 strand.

Economical size of conductor.

This is determined by the discussion headed "Economical transmission voltage." It is shown on page 7 that the economical size of the conductor does not depends upon the distance of transmission line, the formula is:

$$A = \frac{p}{E\cos\theta}\sqrt{\frac{c_e r\ x}{3000 c_c w\ p_c}} \text{ in cir. mils. } \quad \ldots\ldots(1)$$

see page 6 for notations.

Often the problem is however to determine the economical size of the wire to transmit a certain amount of power over given distance with given generated voltage. In that case the equation of economical size of conductor can be derived by equating to zero the derivative of the equation, of the annual expense of conductor and cost of power lost in the conductors, respect to the size of conductor. The equation will be some what complicated unfortunately. The equation which should be used when the recieving voltage and power at generating station are known has been derived by M.W. Franklin in G.E. Review 1910, that is

$$A = \frac{1000(1 - a)^2 p\ r\ L}{E_r^2 \cos^2\theta\ a} \text{ cir. mils. } \quad \ldots\ldots(2)$$

where a = loss of pwer in term of generated power

$$= \sqrt{\frac{3 \times k}{4\ c_e'\ E_r^2 + 3\ k}}$$

$$k = \frac{4000\ p\ c\ r\ w\ L^2}{\cos^2\theta}$$

c'_e = cost per k.w. year, at sub-station, in \$,

the other notation are the same as before.

Both equations give the same results.

Sag and Tension of the conductors.

This problem has been discussed many many times in different form by different engineers but none can evade the equations of the catenary unless approximations are made as for instance in the case given below:

$$T = \frac{w\ l^2}{8\ s} \quad \text{for tension,}$$

$$s = \frac{w\ l^2}{8\ s} \quad \text{for sag,}$$

$$L = l + \frac{8\ s^2}{3\ l} \quad \text{for length between a span,}$$

where T = tension on the conductor,

w = weight of conductor per unit length,

l = length of span,

L = length of the conductor in a span,

s = sag.

It is often necessary, when two supports are at different elevation, to find the lowest point and the sag at given tension of the conductor. That will be found easily by the equation of parabola as follws:

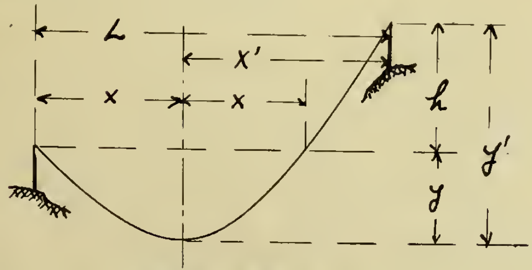


Fig. 5.

The equation of parabola is;

$$x^2 = \frac{2\ T}{w}\ y \ . \ . \ . \ . \ . \ . \ . \ (1)$$

where

T = tension at the lowest point,

w = wt. of cable per unit leng.

$$x'^2 = \frac{2\,T}{w}\,y'$$

but $\qquad h = y' - y$

$$= w/2T\,(x'^2 - x^2)$$

substituting $x' = L - x$, and simplifying,

$$x = \frac{w\,L}{4\,T} - \frac{h}{2\,L},$$

and $\qquad y = \frac{w}{2\,T}\left(\frac{w\,L}{4\,T} - \frac{h}{2\,L}\right)^2$

Table VIII shows the size of the conductor calculated by the equation (1) for different distance and different amount of the power to be transmitted and it also shows the efficiency of the transmission line and % drop of voltage corresponding the conductor given here.

The curves in plate VI are plotted the size of the conductor given in the table VIII, and the curves in the plate VII are plotted the efficiency of transmission line and % drop of voltage given in the table VIII.

Practical example of the transmission lines are given in the Table IX, page 55.

3. Pole and tower. Three kinds of structures are used;

a. Wooden pole construction,

b. Reinforced concret pole construction,

c. Steel tower or Steel pole construction.

The selection of the best type is based upon largely economical considerations. The few important and necessary points will be discussed here; details may be found in almost text books.

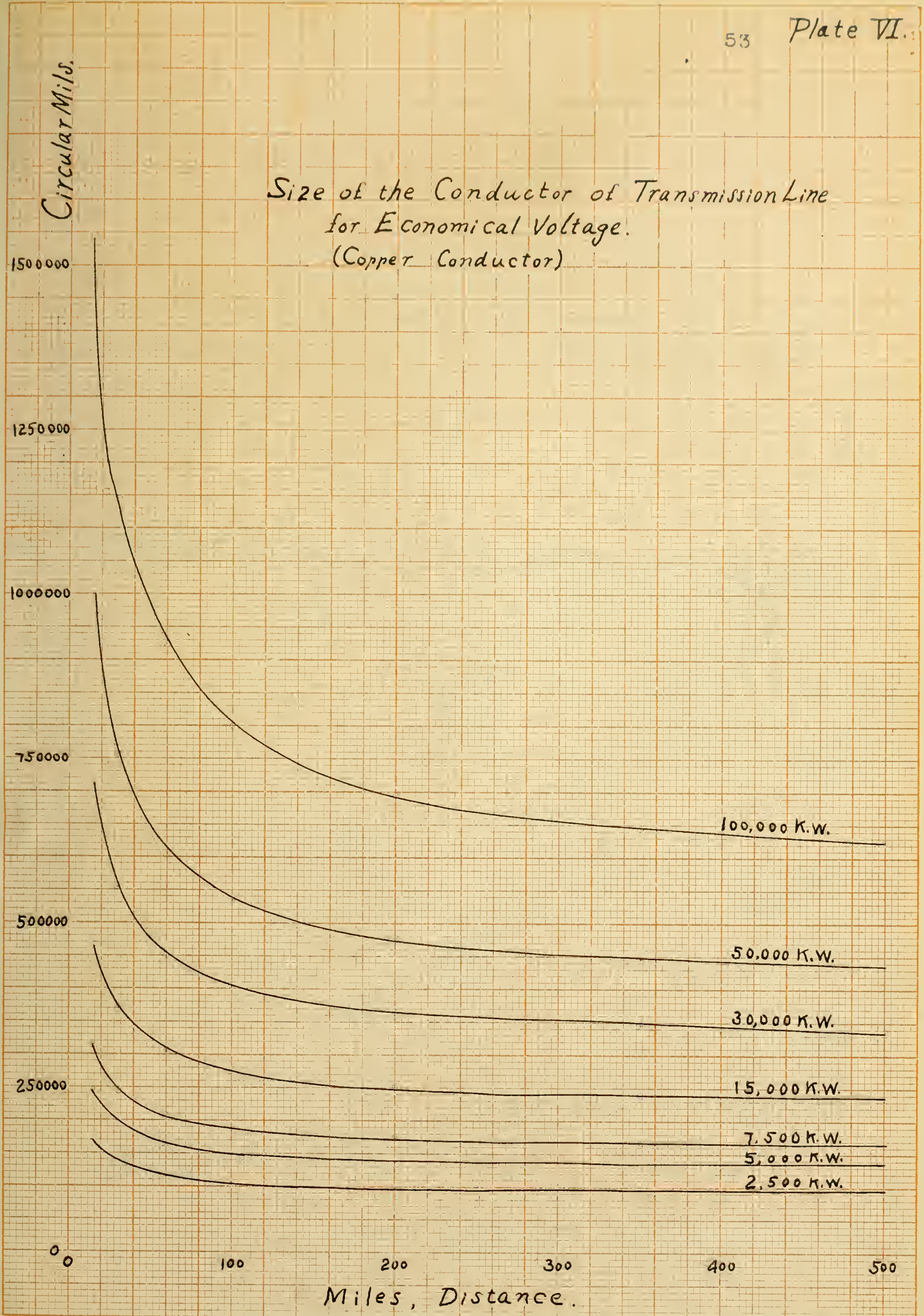
Wooden pole construction. This construction is only adaptable, for high tension transmission systems, when the transmission line passes through or is near well timbered country and therefore

Table VIII.

Efficiency of Transmission line, at normal load of .85 lagging power factor, % drop of vol. and size of conductor.

Distance in miles.	Power to be transmitted, in k.w. 2500	5000	7500	15000	30000	50000	100000
	Efficiency in percentage.						
15	98	98.4	98.6	99	99.2	99.4	99.5
30	96.5	97.5	97.9	98.4	98.8	99.0	99.2
60	94.1	95.7	96.5	97.4	98.1	98.4	98.8
100	90.9	93.5	94.5	96.1	97.1	97.7	98.3
200	83.	88	90	92.8	94.8	96.3	97
350	71.6	79.8	83.3	88.1	91.4	93.3	95.2
500	60.2	71.4	76.6	83.3	88	90.7	93.3
	Percentage drop of voltage.						
15	1.85	1.04	.7	.35	.17	.10	.05
30	2.98	2.17	1.79	1.35	1.01	.83	.63
60	5.08	3.65	3.02	2.21	1.64	1.32	1.01
100	7.7	5.54	4.61	3.31	2.44	1.94	1.45
200	14.4	10.2	8.5	6.07	4.40	3.46	2.53
350	24.2	17.2	14.2	10.2	7.3	5.7	4.12
500	34.0	24.4	19.9	14.2	10.2	7.95	5.7
	Size of the Conductors, in(cir. mils) 10^{-3}						
15	169.5	243.5	316.5	467	713	990	1545
30	136	198	245.5	370	553	754	1157
60	116	167	206.5	303	449	605	923
100	105.5	152	190	274	402	533	798
200	99	139.6	174.8	250	363	475	696
350	95	134.5	167.5	239.5	343	446	646
500	93.2	133.5	163.5	233.5	335.4	436	625

Plate VI.


Size of the Conductor of Transmission Line
for Economical Voltage.
(Copper Conductor)
Circular Mils.
1500000
1250000
1000000
750000
500000
250000
0
0
100
200
300
400
500
Miles, Distance.
100,000 K.W.
50,000 K.W.
30,000 K.W.
15,000 K.W.
7,500 K.W.
5,000 K.W.
2,500 K.W.

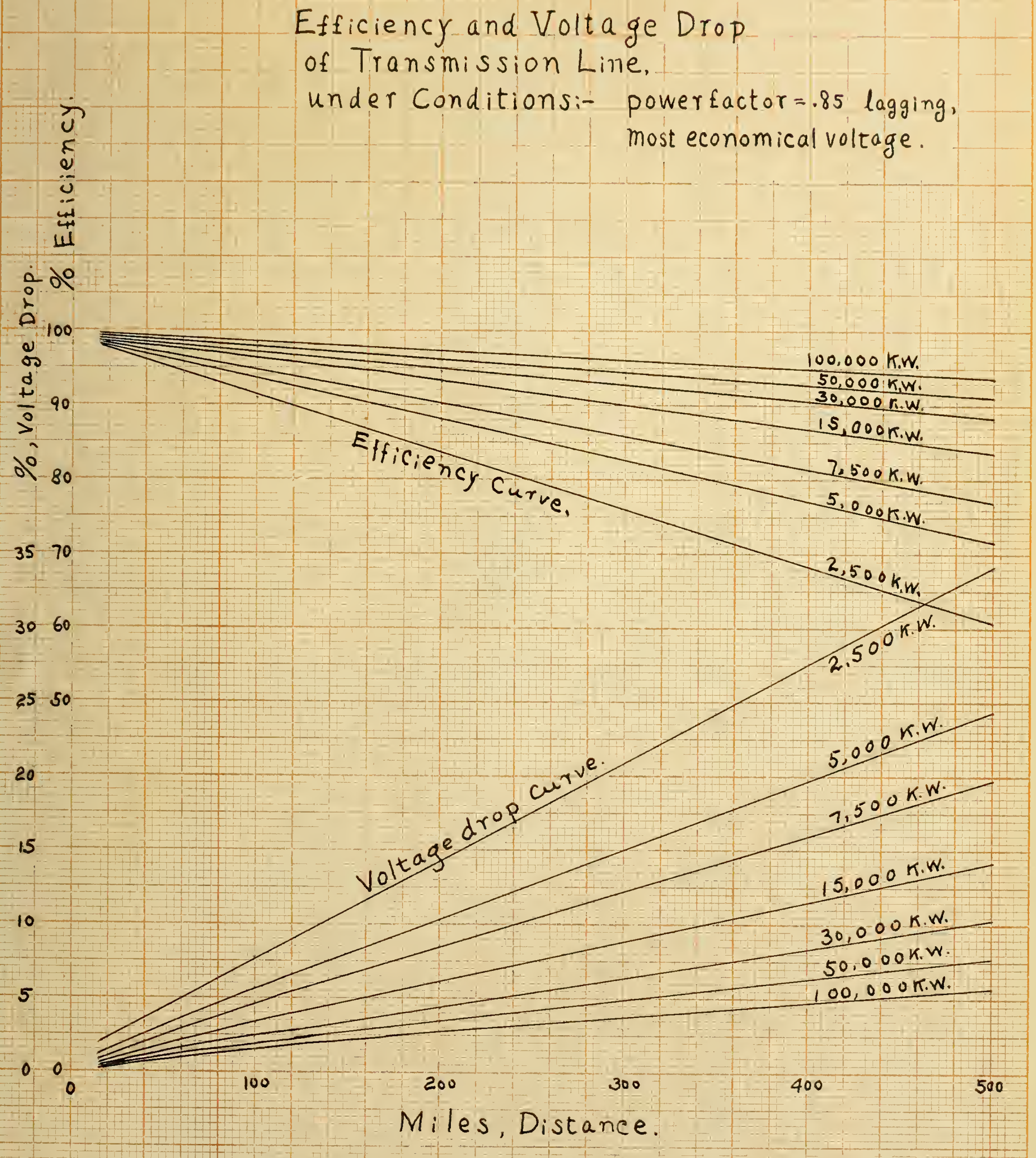

Efficiency and Voltage Drop
of Transmission Line,
under Conditions:- powerfactor = .85 lagging,
most economical voltage.
%, Voltage Drop.
% Efficiency.
Efficiency Curve.
Voltage drop Curve.
100,000 K.W.
50,000 K.W.
30,000 K.W.
15,000 K.W.
7,500 K.W.
5,000 K.W.
2,500 K.W.
2,500 K.W.
5,000 K.W.
7,500 K.W.
15,000 K.W.
30,000 K.W.
50,000 K.W.
100,000 K.W.
Miles, Distance.
0
100
200
300
400
500
0 0
5
10
15
20
25 50
30 60
35 70
80
90
100

Table IX.

Plant.	Trans. volts k.v.	Transmissiom distance, mile, prese.	future.	Power to be trans. k.w.	Spac. bet. cond. inchs.	Hight above ground. ft.	Mater. of cond.	Size of cond.	Solid or strand
A	88	65	110		96	30	.		
B		70			60		Cu.	#1	7 str.
C	140	125	225	9000	204	50	"	#0	" "
D	66	66		10000			"	#2	sol.
E	66	34		9000		*25	Al.	#0 eq.	str.
F	100	154		10000	124	44	Cu.	#0	str.**
G	57	27		6600	54	30	Al.	#000	19 str
H	60	28		5600	72	40	Cu.	#2	sol.
I	100	153		40000	120	46	"	#000	7 str.
J	102	130		10500	124	40	"	#0	" " **
K	60	45		4000	84	30	Al.	#00 eq.	str.
L	33	38.5		5000		40	Cu.	#00	7 str.
M	22	11		3750					
N									
O	110	135	200	7500	120	40	Al.	#000 eq.	str.
P	70	40				44	"	3×10^5 cir.m.	19 st
Q									
R	55	26		10000	72	42	Cu.	#0000	str.
S	100	143			126	*20	"	#00	7 str.
T	100	87		28000	96	*24	Al.	25×10^4 cir.m.	19 str
U	60	39			84		Cu.	#0000	str.
V	63				84	50	Al.	27×10^4 cir.m.	str.
W	60	32				40	Cu.	#0	str.**
X	45	42		3750	72	*28	"	"	7 str.
Y	60				84		"	"	" "

*at the middle of the span. **hemp cored. eq.--equevalent area.

poles may be obtained very chieply. Following figures are a fair guide for the size of the wooden poles and the span.

No. of conductors to be carried.	Size of conductor.	Top dia. of the pole.	Span in feet.
3 or 6	#6 to #1 B.S.	7"	150
3	#0 to #4/0 B.S.	8"	125
6	#0 to #4/0 B.S.	8"	110

Reinforced pole construstion. This is rarely used on account of the difficulty of transportation through rough country.

Steel tower or Steel pole construction. This construction, or more particulary the former, is most widely used in modern development of transmission system. They may be classified in two types, the rigid and the flexible construction. The majority of steel tower belongs to the former. The rigid construction, of course, is safe under almost any possible disturbance, but it is very expensive. Most engineers adapts this construction and design towers to withstand the stress due to the breakage of one wire or two wires or even more, according to the amount of money that they felt could be spent on the line construction. Tower designed under these assumptions have seems to me too great factor of safty because the breakage of a conductor is very rare indeed, if the cable has been strung properly. Flexible towers have been recommended,recently, to satisfy economy without reducing the safty. This type will probably be much used in the future. The writer is inclined to favor them, especialy when heavy ground wires or a single ground wire is attached rigidly at each pole. The interval of strain tower in flexible construction depends on local condition - nature of country, number of angles of the line,etc., - but one strain tower every mile or mile and a half may be practi-

cable in tangent line. The flexible construstion which involves one or more ground wires attached rigidly at each pole is preferable from the point of view of lightning protection as well as for mechanical reasons. The flexible construction must satisfy following condition.

$$n\,T + n_1 T_1 + \frac{3\,d\,E\,I}{H^3} + n_2 t = n_2 T_2 + n\,T'$$

where n = no. of ground wires,

n_1 = " " conductors in the defect span,

n_2 = " " " " the normal span,

T, T' = tension of ground wire in the defect span,and next sapn respectively,

T_1, T_2 = tension of power conductor in the defect span and next sapn respectively,

t = force necessary to deflect insulator,

d = deflection of structure of the defect span at the point where resultant force acted,

E = moduluse of elasticity of structure,

I = moment of inertia of structure,

H = hight of the point, force acted, above the ground.

No earth yield and no slip of wire at tie are assumed. The proper dimensions of the flexible construction will be obtained from the above equation, assuming a certain number of spans affected by breakage one or more of wires in one span.

Economical span. The economical span is that which gives a minimum of annual charge for the investment of all structures (including erection expense) and insulators. Geographical conditions, climatic condition, also govern the length of span. Sometimes the economical size of the conductor may limits the span,

that is the conductor may be so small as to require a shorter distance between towers than would otherwise be economical.

Table X shows examples of line construction. (page 59.)

4. Insulator.

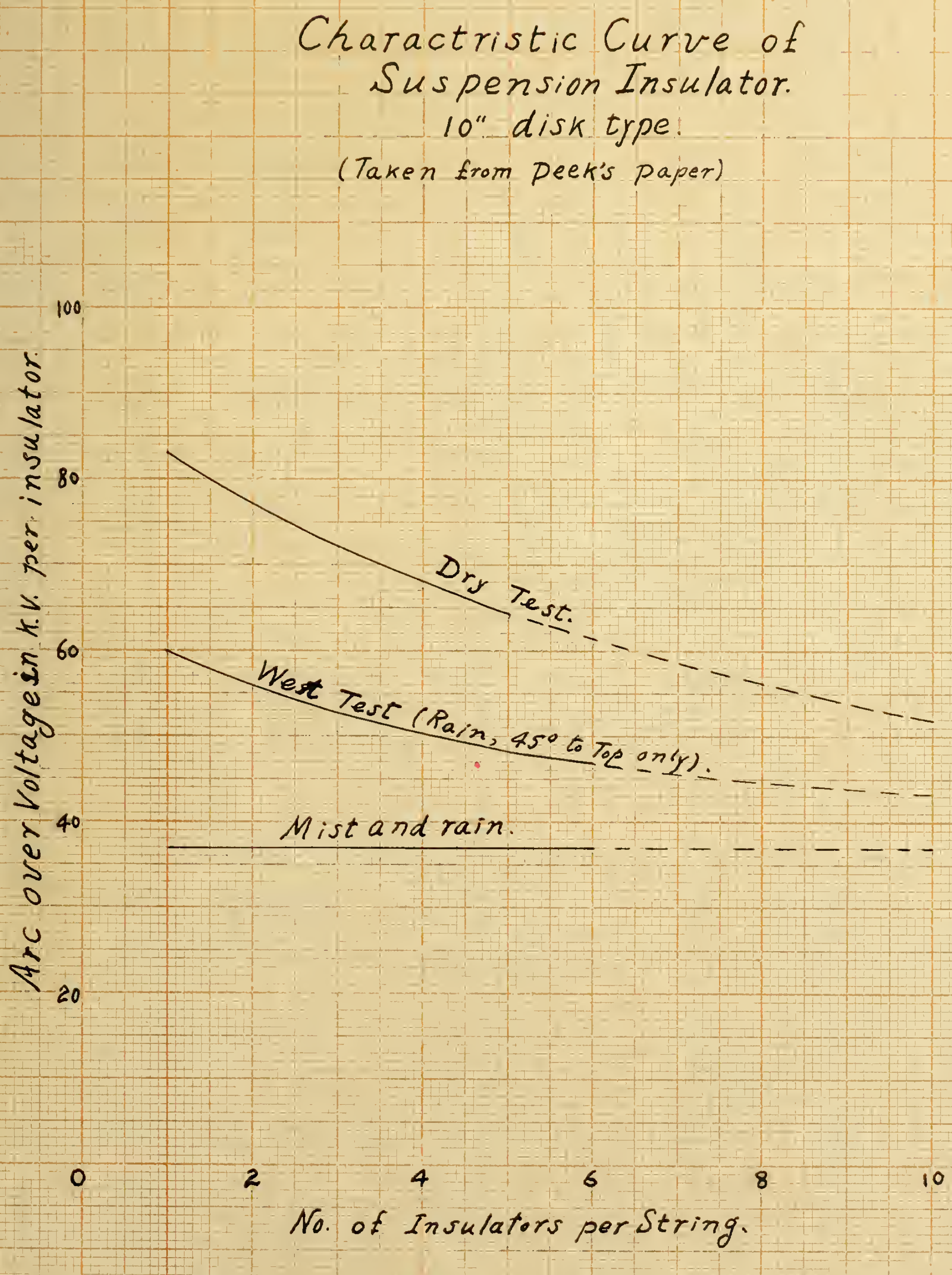
Pin type insulator may be used for up to 80 k.v. according to manufacturer's claims but it safer and more economical to use suspension type insulator when the voltage is more than 60 k.v. The cost of the pin type insulator increases proportionally to the cube of the voltage while the cost of the suspension type is about proportional to the voltage. In modern practice, the suspension type of insulators is used even for voltages lower than 60 k.v. Since the suspension type of insulator is manufactured for various voltage up to 100 k.v.(arc over voltage) frequently a string of suspension type insulators are used in series for the highest voltages. The practical question is how many insulators should be used. This is answered in the curves in the plate VIII, page 60, which show typical electrical characteristic of suspension insulators. Details of the electrical characteriatics of are thoroughly discussed, theoretically and experimentaly, in Proceeding of A.I.E.E. May, 1912 by Peek and in G.E. Review April, 1913 by F.F. Brand. The suspension insulator may be used as a strain insulator, and it is so used almost usually in modern practice. Since in such a cases,a string of insulators are used and the string is pulled in a horizontal position they are exposed to the worst condition against rain therefore its wet arc over voltage should be considered. Practical examples are given in the table XI.

Table X.

s.t.--steel tower.
w.p.--wooden pole.

Plant.	Trans. volts k.v.	Kind of struct.	Span in feet.	Condition of design.	No. and size of conduc.	Overall hight in ft.	Weight in lbs.
A	88	w. p.				39	
B							
C	140	s.t. 4 legged	500		3, #0	54	
D	66	" " " "	410	all wires broken.	6, #2	40-60	
E	66	""" "	550	11000 lbs. h. s.	6, $\#0_{eq.}$	60	3200
F	100	"" " "	300-2900	25000 lbs. *	3, #0	50	2200
G	57	w. p.	130		3, #000a	45	
H	60	s.t. 4 legged.	600		6, #2	60	3750
I	100	" " "	750		6, #000		
J	102	" " " "	600		3, #0		
K	60	w. p.	300		6, $\#00_{eq.}$	50	
L	33	" "	200		3, #00	40	
M							
N							
O	110	s.t. 4 legged.	550	20000 lbs. h. s. *	6, $\#000_{eq.}$	65	4000
P	70	" " " "	500		6, $3\times10^{5}\text{a}_{\text{cir.m.}}$	62.5	
Q							
R	55	s.t. H frame.	400		6, #0000	60	
S	100	s.t. 4 legged.	600		6, #00		
T	100	" " " "	520	*15000 lbs.	6, $25\times10^{4}\text{a}_{\text{cir.m.}}$	70	4800
U	60		500				
V	63	w. p.	650		3, $27\times10^{4}\text{a}_{\text{cir.m.}}$	55-85	
W	60	s.t. 4 legged.	660	2000 lbs. h. s.	6, #0	60	2510
X	45	" " " "	600	2500 " " "	6, #0	65	4000
Y	60	w. p.			3, #0	50	

*tested ulyimate., h.s.--horizontal stress at the top., a--alumi.



Charactristic Curve of
Suspension Insulator.
10" disk type.
(Taken from Peek's paper)
Arc over Voltage in k.v. per insulator.
100
80
60
40
20
Dry Test.
West Test (Rain, 45° to Top only).
Mist and rain.
0
2
4
6
8
10
No. of Insulators per String.

Table XI.

Plant.	Trans. volts k.v.	Type of insula.	No. of insula. per string.	Volts per ins. k.v.	Outside dia. of insu.	No. of ins. per strain string.
A	88	suspen.	4	22		
B		"	2		15"	
C	140	"	10	14	10"	
D	66	Pin			15"	
E						
F	100	Suspen.	4	25	10.25"	
G	57	Pin				
H	60	"				
I						
J	102	Suspen.	6	17	10"	
K	60	"	2	30		
L	33	Pin				
M						
N						
O	110	Suspen.	8	13.8		10
P	70	"	5	14.0		6
Q						
R	55	Pin				
S	100	Suspen.	4	25	14"	5
T	100	"	7	14.3		8
U						
V	63	"	4	15.8		
W	60	"	3	20	10"	4
X	45	"	3	15	10"	
Y	60	Pin.				

V. Regulation and Protection.

1. Regulation.

Voltage regulation. Constant voltage is demanded in order to obtain most efficient operation and is especially necessary when lighting is done directly or through transformers from the high tension line. The generator voltage can be kept constant by means of Tirell regulator. Frequently, however, this is not desirable - often the power is supplied to a number of feeders each demanding a different voltage. In such cases feeder regulator are used or more often the voltage of each feeder is cotrolled from or at the recieving circuit. This being done either by induction regulator or by transformer of variable ratio or by "phase controll" the principle of which is now well known to engineers. Briefly, let

$$e = \dot{E} - \dot{I}\,\dot{Z}$$

where E = voltage per pkase at generator,

e = " " " " recieving end,

$\dot{I}$ = total current in line conductor,

$\dot{Z}$ = impedance per phase.

The generator voltage being kept constant, the line drop, $E - e$, must be kept constant in order to keep the recieving voltage constant. This can be done by means of the supplying lagging current for the light load and leading current for heavy load. The synchronous motor with automatic field regulator suffices for such controll. The details of such voltage regulation by means of

synchronous motors, equipped with automatic voltage regulators, is discussed thoroughly in a article by Dr. berg, printed in the G.E. Review of September, 1912.

Power factor regulation. Because the line current varies indirectly with the power factor, it is a favt that short transmission at low power factor are either expensive because of the greater amount of line copper necessary or are inefficient.

The power factor of course is unity when the inductive reactance and the condensive reactance of the system are equal. For this reason, there is really very little difficulty with power factor in long high tension transmission line because the charging current there is usually considerablly and more or less automaticaly balances the lagging current taken by transformers, induction motors or under-excited synchronous motors.

Switch board apparatus. Switch board apparatus are now standardized and for that reason require no description.

The type of switch is however an important point, should it be automatic or non-automatic? It appears most conservative to do the switching in the low voltage circuit, especially of the load is small. The oil switch has been greatly improved lately and appears to be giving satisfaction in high tension service. Some engineers in charge of modern high tension long distance transmission system claim that actual experience has shown that the improved oil switch works as satisfactorily and with a little trouble on these lines as on the low tension system, even when opening short circuit on the high potential side. As a matter of fact, three different arrangements are used in practice as follows:

First. Automatic oil circuit breaker, with or without time limit

over load relay, these on both the high and the low potential side of the circuit.

Second. Automatic oil circuit breaker, with or without time limit over load relay, on the low potential side, and non-automatic oil switch on the high potential side.

Third. Non-automatic oil switch on the low potential side and automatic oil circuit breaker, with or without time limit over load relay, on the high potential side.

Examples are given below:

First case.		Second case		Third case.	
Designation of plant.	Trans. vol. in k.v.	Designa. of plant.	Trans.vol. in k.v.	Designa. of plant.	Trans. vol. in K.v.
E	66	C	140	R	55
D	66	K	60	U	60
I	100	Q	57		
N	66	S	100		
T	100				
V	63				
P	70				

One special case shoul be noted. At the Shoshone plant of Central Colorado Power Co., where power is transmitted 153 miles at 100 k.v., only low tension switches with automatic device have been installed in the power station and high tension switches have been installed in the substation only.

2. Lightning protections.

"Lightning" is used here ina broad sense and covers not only phenomena due to atmospheric electricity but also phenomena caused by disturbances of the power itself in the circuit such as are

caused by sudden changes of the load, spar discharges through some weak point of the circuit, etc.

The phenomena ob abnormal voltage and abnormal frequency in electric circuits may be devided into three class, as suggested by Dr. Steinmetz;

1. Gradual electric charge,
2. Impulse or traveling wave,
3. Oscillation and surge.

The collection of a static charge from the surrounding medium, an unbalancing of the circuit, the existence of higher harmonics in the e.m.f. wave, etc., introduce phenomena of the first class.

A direct or secondary lightning stroke on the line, electrostatic induction from charged clouds, an arcing ground of one phase in an insulated neutral system, sudden changes of load, etc., are causes of the second class of phenomena.

When both capacity and inductance are presenced oscillations will appear as the results of any disturbance, due to the possible interchange of electro-static and electromagnetic energy. This transfer is necessarily inefficient and the circuit will therefore regained its equilibrium because of the dessipation of the energy introduced by the disturbance, provided, of course, that the disturbance itself is of short duration. Should this not be true and if the impulse are properly timed it is possible for the ~~interchange~~ amplitude of the oscillations to increase, the interchange of energy developing into great surges which must be overcome or the system will be wrecked.

A gradually increasing electric charge on a conductor causes

its voltage to rise . If the charge becomes too great, the insulation will break down, a discharge taking place which will introduce an impulse and oscillation. This discharge is usually accompanied by dynamic current, therefore serious damage may result.

The fundamental equation of transients is,

$$\frac{i^2L}{2} = \frac{e^2C}{2},$$

or $$e = i\sqrt{L/C},$$

and $$i = e\sqrt{C/L},$$

where L = inductance of the circuit,

C = capacity of the circuit,

e = maximum transient potential,

i = " " current.

From this it is seen that the highest oscillating potential will be produced when short circuit occurs. A more accurate equation of surge potential has been given by Dr. Steinmetz, in which the higher harmonics of the fundamental wave of the oscillation are considered.

The fundamental frequency of oscillation, N_o, is expressed by:

$$N_o = \frac{1}{4\sqrt{L_oC_o}},$$

and all its odd higher harmonics may be expressed by:

$$N = (2k - 1)N_o,$$

here L_o = inductance per unit length of the circuit,

C_o = capacity " " " " " ,

k = any integer.

Then the surge potential is:

$$e = i\sqrt{L/C}\,(1.26\cos\omega\sin\phi + 0.40\cos 3\omega\sin 3\phi + 0.22\cos 5\omega\sin 5\phi + 0.13\cos 7\omega\sin 7\phi + 0.07\cos 9\omega\sin 9\phi + \text{-- -- - -})$$

e = transient voltage,

i = short circuit current,

$\phi = 2\pi Nt$

$\omega = \pi u/2 \cdot l$

l = length of the line,

u = distance along the line from point where the short circuit occured, as the zero point.

The arcing between line or between one of lines and ground, which may occur because of defective insulation in a system with insulated neutral, produce somewhat of the same effect as the surge caused by a short circuit. Due to the high resistance of the arc circuit the circuit breakers do not open at once, unless a special arc suppresser is used, which is not often the case. The arc produces impulses in rapid succession, according to the frequency of the generated power. These impulses will introduce high frequency oscillations and thereby cause the potential to an enormous magnitude.

Serious disturbances because of atmospheric electricity are, of course, those due to a direct stroke of the lightning discharge and to statical induction by a lightning discharge to ground or between clouds. Statical induction by the charged cloud or by the lightning discharge depends on the distance of the line from the source of the induction. The disturbance ib usually is not serious, except when the induction takes place near to the station. The distribution of such a disturbance is about the same as that of a short circuit or an arcing ground.

Lightning arresters must be so constructed that they will discharge abnormal voltages between line and ground without permit-

ting a flow of dynamic current to follow.

The earlier lightning arresters were chiefly of the non-arcing metal multi-gap type and the horn type air gap with non-inductive high resistance in series in each case, or sometimes with the addition of a grounded condenser which served to absorbe the hgih frequency power. Such types do not work satisfactorily on modern high potential lines and are rapidly disappeared from the commercial uses. This has been especially true since the application of aluminum cells to lightning protection has been invented. The writer has found omly one example of the use of horn type air gap arresters with water jet resistance in series out of twenty five recent developments,studied, all of rest using aluminum cells in series with the horn gap. The potential in the one case found was 60 k.v. In recent practice the horns are almost always installed outside the station, on the roof of the building or on a special structure; in some cases the stacks of aluminum cells also are installed outside of the building.

Two auxiliary but effective devices in the protection against lightning are the ckoke coil and the over head ground wire.

The choke coils serve two purposes in the protection against lightning, one is its natural and well known function, as a reactance coil, of keeping the high frequency disturbance out of the apparatus. The other is its appearance as the end coils of the transformer, protecting the coils themselves against the low frequency surge. At the first instant, the entire potential,which is entering, must be sustained by the first coil of the circuit, a moment later one half of the potential is applied to each of the first and second coils, and so on. It is evident that choke

coils can be sufficiently insulated to withstand these abnormal potentials much more conveniently and effectivly than can the end turns of the transformer. As the same time, there is one decided objection to the use of the choke coil in very large high tension transmission systems, in that the coil tends to reflect back the high frequency which may be originated inside of the large high tension transformer, having the distributed capacity, and thereby a dangerous voltage may be created in the transformer coil. For this reason, in localities where little or no atmospheric disturbance is known, it is found to be better practice to omit the choke coil. The White River plant of the Puget Sound Light and Power Co. is an example where no choke coil and no over head ground wire is used, lightning itself being almost unknown in the region to which power is supplied from this plants.

Effects of over head ground wires. The effectiveness of over head ground wires as a protection against any disturbance by atmospheric electricity has been recognized practically as well as theoretically. Such over head wires, of course, must have sufficient mechanical strength and must be properly located with respect to the power conductors. An proper arrangement of several ground wires, obviously, will afford much better protection than a single line, but the effect does not increased in proportion to the number of wires used. Practical examples are given in table XII, the following page.

A theoretical investigation, showing how the distribution of the statical potential is affected by the ground wires, is given below.

The charged cloud may be assumed as like as a line charge.

Table XII.

	Designation of plant.	Transmission voltage, k.v.	Diameter of ground wire.
No ground wire.	K	60	
	L	33	
	R	55	
	Y	60	
Single ground wire.	A	88	3/8"
	B		
	D	66	1/4"
	H	60	3/8"
	P	70	"
	S	100	"
	V	63	"
	W	60	"
Double ground wires.	E	66	"
	F	100	1/4"
	J	102	3/8"
	T	100	"
	X	45	5/16"
Tripple ground wires.	O	110	5/16"

Then the problem will be very much simlified.

$$e = 2q \log_e \frac{2h}{r} + 2Q \log_e \frac{D}{d}$$

where,

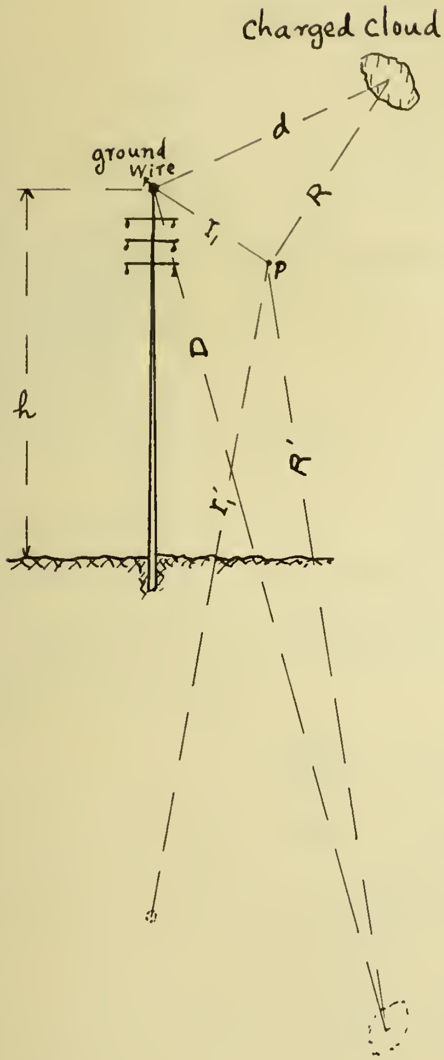


Fig. 6.

e = potential induced when the wire is not grounded,

q = charge in the wire,

r = radius of the wire,

Q = charge in the cloud.

Since the wire is grounded,

$$0 = 2q \log_e \frac{2h}{r} + 2Q \log_e \frac{D}{d}$$

and

$$q = - \frac{Q \log_e \frac{D}{d}}{\log_e \frac{2h}{r}} .$$

The potential at any point p in space is ;

$$e_p = 2q \log_e \frac{r_1'}{r_1} + 2Q \log_e \frac{R_1'}{R}$$

$$= - 2 \frac{Q \log_e \frac{D}{d}}{\log_e \frac{2h}{r}} \log_e \frac{r_1'}{r_1} + 2Q \log_e \frac{R'}{R} .$$

D, d, h, and r are constants which depends on the position and size of the conductor and the position of the charged cloud. Thus equation for e_p becomes:

$$e_p = 2 Q \log \frac{R'}{R} + k \log \frac{r_1'}{r_1} .$$

Q, R', R, d, D, are not known, but the equation indicates how the potential will be distrobuted when the ground wire is used. Assume for instance that the potential gradient is straight line within the reasonable limits above the ground, when no ground wire

exists. Then

$$2\ Q \log \frac{R'}{R} = c\ H\ ,$$

where c = constant,

H = height of the point above ground,

and e_p becomes

$$e_p = cH - k \log \frac{r_1'}{r_1}\ .$$

The folloeing numerical examples are given to illustrate the above theory.

Example 1.

Great Western Power Co.'s 100 k.v. line:

Diameter of the ground wire = .375",= $2r$,

Hight of the ground wire above ground = 76'= h.

Assuming the potential at the ground wire,when it is not grounded, to be 100,

$$c = \frac{100}{76} = 1.32.$$

The potential must be zero, wire is grounded, at $r' = 2\ h$, and $r_1 = r$. Since $\log_{10} 2h/r = 3.989$, $k = 100/3.989 = 25$, and

$$e_p = 1.32\ H - 25 \log \frac{r'}{r}\ .$$

Results calculated from this equation are plotted in the curve in the upper part of the plate IX, page 75. The dotted line in the figure represents the distribution of the potential, when no ground wire exists, in relative value.

Example 2.

Ontario Power Commission's 110 k.v. line:

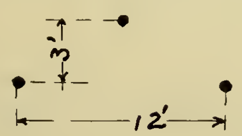


Fig. 7.

Dia. of the ground wire $= 2r = 3.12"$,

Three ground wires are used as in Fig. 7 , the hight of the lowest wire above ground = h = 54'.

By the same reason as before the following equation has been derived.

$$e_p = c\ H - k\ \log \frac{r_1'}{r_1}\frac{r_2'}{r_2}\frac{r_3'}{r_3} .$$

Here r_2, r_2', r_3, and r_3' are the distance of the point in space from the second and third ground wire and its image respectively. Assuming the potential, when no ground wire exists, to be 100 at 50 ft. above ground, c = 2. To find the value of k equate the above equation to zero, substituting the values of r_2', r_2, r_3', and r_3 at $r_1 = r$ and $r_1' = 2h$. It is k = 100/6.136 = 16.3. Therefore,

$$e_p = 2\ H - 16.3\ \log \frac{r_1'}{r_1}\frac{r_2'}{r_2}\frac{r_3'}{r_3} .$$

Results calculated from this equation are plotted in the lower part of the plate IX, page 75. The dotted line in the figure represents the same as before.

Example 3.

Shawinigan Fall Power Co.'s 100 k.v. line:

Dia. of the ground wire = 2r = .375",

Two ground wires are used at 70 ft. above ground, and distance between them is 32'.

As before,

$$e_p = c\ H - k\ \log \frac{r_1'}{r_1}\frac{r_2'}{r_2} .$$

Assuming the potential, when no ground wire exists, to be 100 at 70 ft. above ground, then c = 100/70 = 1.43. and as before, k = 100/4.604 = 21.7 . Therefore,

$$e_p = 1.43\ H - 21.7\ \log \frac{r_1'}{r_1}\frac{r_2'}{r_2} .$$

Results calculated from this equation are plotted in the

curve in the upper part of the plate X, page 76. The dotted line represents the same as before.

Example 4.

Great Fall Power Co.'s 100 k. v. line:

Dia. of the ground wire = 2r = .375"

Two groud wires are used at 50 ft. above groud, and dis- dance between them is 10 ft.

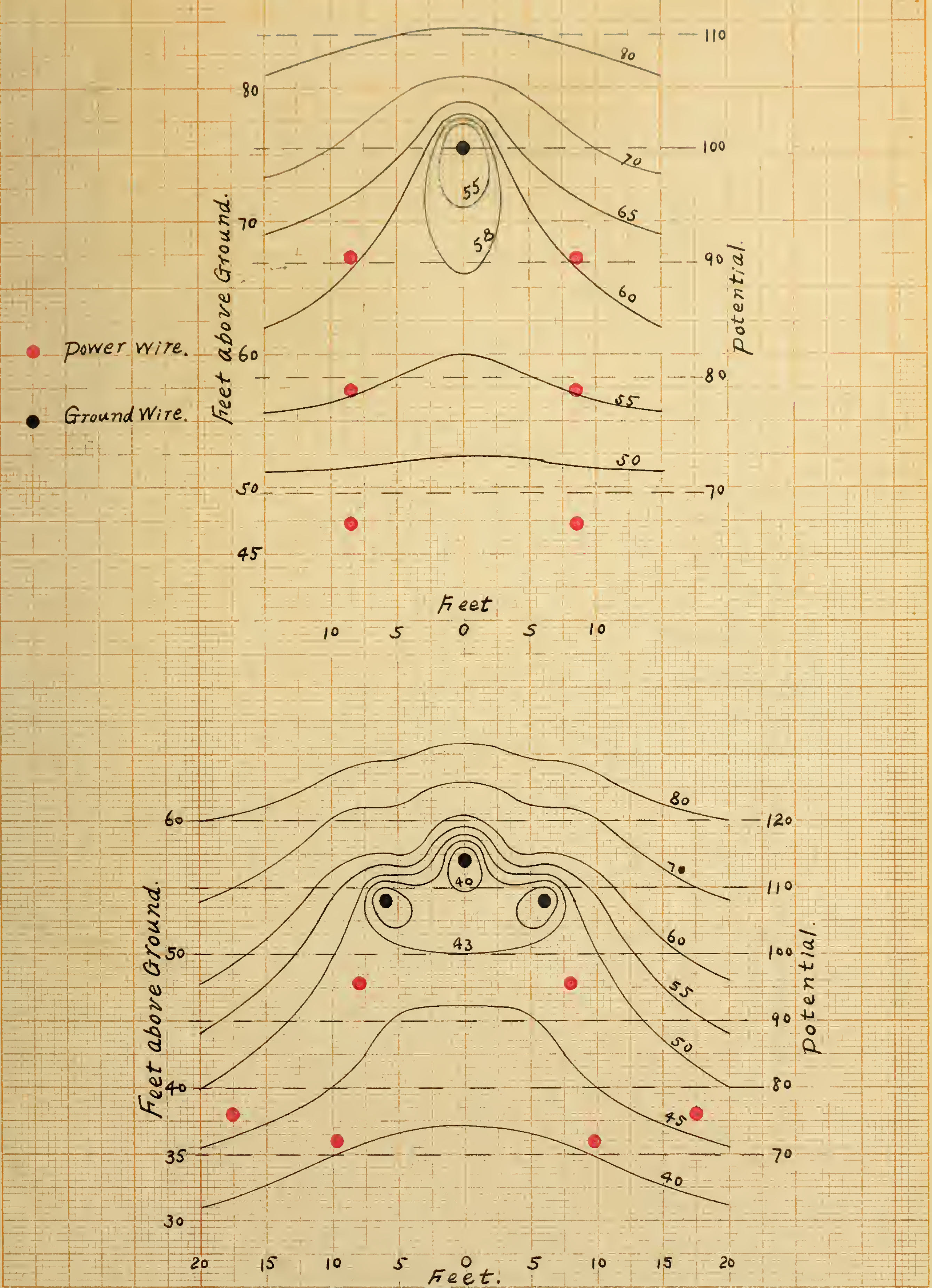
As before we get

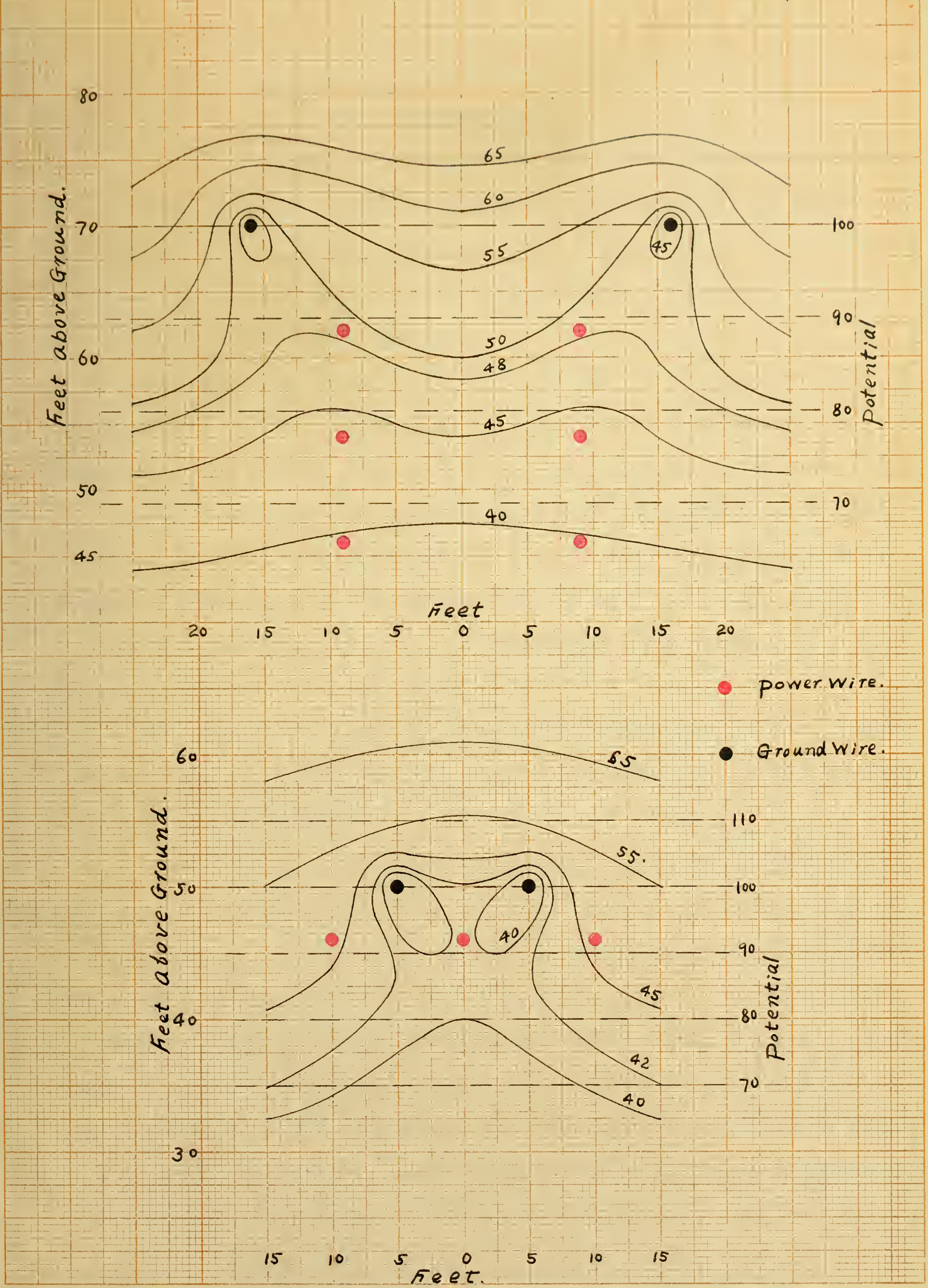
$$e_p = 2\ H - 21 \log \frac{r_1'}{r_1} \frac{r_2'}{r_2} .$$

Results calculated from this equation are plotted in the curve in the lower part of plate X, page 76. The dotted line represents, also, the same as before.

While the present method of protecting transmission lines against damage by lightning, using horn gaps and aluminum cells, appears to be very satisfactory in its operation, it is expensive in very high potential systems and engineers continue in the search for new methods. The phenomena of corona suggests one possibility to these engineers. Theoretically, for a given length of a certain size of conductor, properly spaced with reference to the rest of the line, there will be a definite or critical voltage above which a considerable part of power will be discharged by corona. The amount of power discharged increases as the potential continues to rise above the critical voltage. In the Shoshone plant of the Central Colorado Power Co. it has been found that any lightning disturbance which occurs one side of the highest elevation of the transmission line, which is in 13,700 feet above see level, does not travel to the station on the other side over that peak.

Plate IX.


Power wire.
Ground Wire.
Feet above Ground.
Potential.
Feet
80
70
60
50
45
110
100
90
80
70
80
70
65
60
58
55
55
50
10
5
0
5
10
Feet above Ground.
Potential.
60
50
40
35
30
120
110
100
90
80
70
80
70
60
55
50
45
40
40
43
20
15
10
5
0
5
10
15
20
Feet.



Feet above Ground.
80
70
60
50
45
65
60
55
50
48
45
40
100
90
80
70
Potential
Feet
20 15 10 5 0 5 10 15 20
Power Wire.
Ground Wire.
Feet above Ground.
60
50
40
30
65
55.
40
45
42
40
110
100
90
80
70
Potential
15 10 5 0 5 10 15
Feet.

VI. Conclusion.

It can be seen from the precceding study that Hydro-electric development has made great progress during the last few years and that is still advancing, and the writer blieves that power transmission to New York city from Niagara Falls may become an accomplished fact in the near future.

The problems which should be studied in considering the development of long distance hydro electric transmission, have been taken up in this thesis, may be summerized as follows:

The improvment of the efficiency of the hydraulic prime mover is greatly to b desired because it only averages 85 % in present practice, while no large margine exists for the improvement of electric machines since it now averages 96 % joint efficiency of the generator and transformer.

The study of the high potential transformer is most important because it is the weakest link in the high potential transmission system at present.

The Study of the conductor is necessary, since the investment in the transmission line is great owing to the high cost of the conductor. The use of aluminum conductors sometimes makes the expense slightly less but the gain is always very small and furthermore the aluminum conductor has some disadvamtages. Therefore, if a new conductor material which has good conductivity and high tensile strength and which is cheaper were invented it would be a great factor in the development of long distance transmission.

Finally the study of corona is important. Either its pre-

vention or its utilization may be attempted. For the prevention of corona loss Dr.Berg's suugestion may prove of value, viz. that close together conductors of the same phase be put instead of running each circuit separately. See Fig. 8. This method is obviously effective for the prevention of corona loss.

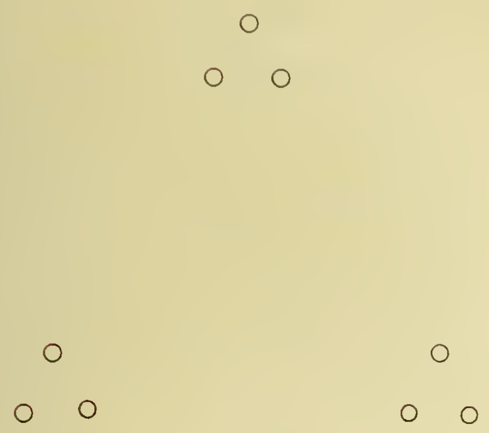


FiG. 8.

The utilization of corona loss as a protection from abnormal voltage, which is briefly mentioned in the last part of the section on lightning protection, is also an important matter for consideration.

APPENDEX.

Name and location of the Hydro-electric systems, and its Abbreviature.

		Year, installed
A.-	Appalachian Power Co. Fries, Va.	1912.
B.-	Arizona Power Co.	1909.
C.-	Au Sable Electric Co. Mich.	1912.
D.-	Connecticut River Power Co. Vernon, Vt.	1910.
E.-	Central Georgia Power Co. Lloyd Shoals, Ge.	1910.
F.-	Central Colorado Power Co. Colo.	1909.
G.-	Mount Hood Hydro-electric Devel. Portland, Ore.	1912.
H.-	East Creek Elec. Light and Power Co. Ingham, N.Y.	1911.
I.-	Great Western Power Co. Cal.	1909.
J.-	Great Falls Water Power Co. Rainbow Fall, Mont.	1910.
K.-	Jordan River Power development. Wash.	1912.
L.-	Minidoka Project.(U.S. Reclamation service.)	1910.
M.-	Mohawk Hydro-electric Power Co. Ephratah, N.Y.	1911.
N.-	Nothern California Power Co. Cal.	1910.
O.-	Ontario Power Commission. Niagara, Canada.	1911.
P.-	Pennsylvania Water Power Co. Macall Ferry Pa.	1910.
Q.-	Portland Ry. and Light Co. Portland, Oregon.	1911.
R.-	Puget sound Traction and Light Co.	1911.
S.-	Southern Power Co. Great Falls, S. Carolina.	1910.
T.-	Shawinigan Power Co. canada.	1912.
U.-	Seattle Minicipal Light and Power Co. Seattle Wash.	'11.
V.-	Washington Water Power Co. Little Falls, Wash.	1911.
X.-	Utah Light and Railway Co.	1912.
Y.-	San Joaquin Light and Power Co. Fresno, Cal.	1911.